THE INFLUENCE OF CONTROLLED ENVIRONMENTAL CONDITIONS ON THE POTENTIAL DURABILITY OF CONCRETE

by

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DECLARATION

I declare that this thesis is my own, unaided work. It is being submitted for the Degree of Masters of Science in Engineering in the University of Stellenbosch. It has not been submitted before for any other degree or examination in any other University.

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ABSTRACT

The primary objective of this investigation was to determine the influence of temperature, relative humidity and wind speed on the potential durability of OPC concretes. Three concrete grades were investigated, and the samples were wet cured for periods of 1, 3 or 7 days before the start of exposure. The exposure temperatures investigated were 20, 28 and 35°C (at 50% RH), and the relative humidities were 54%, 66% and 82% (at 20°C). The investigation of wind speed was limited to 5,6 m/s. Moisture losses from the concrete samples were monitored during the drying period, and the durability index tests were used to indicate the quality of the covercrete.

The quality of poorly cured concretes were impaired at elevated temperatures, while well cured concretes were able to retain their moisture and benefit from the increased rate of hydration. Results obtained from concretes exposed to 82% relative humidity were similar to fully cured results. Below this value, the results obtained were insensitive to relative humidity. The influence of wind speed was insignificant. Wet curing for at least 3 days was necessary to obtain durable covercrete, except in the case of high relative humidity exposure conditions.

A theory was formulated for the drying processes of hardened concrete, which can be used to calculate the porosity characteristics of the covercrete, when exposed to varying relative humidities and a constant temperature of 20°C. This theory could be related to the durability indexes obtained from the drying regimes of varying relative humidity and constant temperature.

OPSOMMING

Die doel van hierdie projek was om die invloed van temperatuur, lugvogtigheid en windspoed op die potensiële duursaamheid van OPC beton te ondersoek. Drie verskillende betonsterktes is ondersoek, en die monsters is nabehandel vir 1, 3 of 7 dae, voor blootstelling aan die omgewing. Die blootstellingstemperature wat ondersoek is, was 20, 28 en 35°C (by 50% relatiewe lugvogtigheid), en die relatiewe lugvogtighede was 54, 66 en 82% (by 20°C). Die ondersoek van windspoed was beperk tot 5,6 m/s. Die massaverliese van die betonmonsters is gemonitor tydens die blootstellingstydperk, en die duursaamheidsindekstoetse is gebruik om die kwaliteit van die beton aan te dui.

Die kwaliteit van beton wat nie behoorlik nabehandel is voor blootstelling nie, is benadeel deur hoë temperature. In die geval van goeie nabehandeling, het die betonmonsters hulle interne vog behou en gebaat by die hoër tempo van sement-hidrasie. Die resultate van monsters wat blootgestel is aan 'n lugvogtigheid van 82%, was naastenby dieselfde as monsters wat ten volle nabehandel is. Benede hierdie waarde was die resultate nie sensitief ten opsigte van lugvogtigheid nie. Die invloed van windspoed was gering. Nabehandeling vir ten minste 3 dae was noodsaaklik, ten einde te verseker dat die beton genoegsame duursaamheidskwalitiete ontwikkel (uitsluitende die geval van hoë lugvogtighede tydens blootstelling).

'n Teorie is ontwikkel om die uitdrogingsproses van verharde beton te beskryf, wat gebruik kan word om die porositeitseienskappe van die beton te bereken. Die model neem blootstellingstoestande van verskillende lugvogtighede en 'n konstante temperatuur (van 20°C) in ag. Daar was 'n goeie verband tussen die teorie en die resultate van die ondersoek na die invloed van lugvogtiheid.

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GLOSSARY OF SYMBOLS

Symbol	Description
α	Degree of hydration (mass of combined water / mass of cement, or %)
α_e	Effective degree of hydration (hydration at pore relative humidities > 95%) (%)
$\partial m/\partial t$	Rate of flow (m^2/s)
$\partial P/\partial z$	The pressure gradient in the direction of flow
ρ	Density of the liquid (1000 kg/m^3 for water)
τ	Surface tension of the liquid (0.072 newton/m for water)
A	Cross sectional area of the sample (m^2)
a_i	Coefficients of equation 2-7
c	Cement content of a concrete mix (kg/m^3)
C	Weight of cement (kg)
CAZ	Curing-affected zone
d	Thickness of the specimen (m)
d_{ex}	Depth from the exposed surface (mm)
D_p	Diffusion coefficient (m^2/s)
dp/dx	Vapour pressure potential (m/m)
dq/dt	Rate of flow (m^3/s)
E	Rate of evaporation ($kg/m^2/hr$)
e_f	OPC replaced with pfa or ggbfs (%)
g	Acceleration due to gravity
$GGBS$	Ground granulated blastfurnace slag
HCP	Hardened cement paste
K	Coefficient of permeability (m/s)
M	Molecular mass of the liquid (0.018 kg/mole for water)
n	Number of time intervals, used in calculating weighted average conditions of conditions in the environmental chambers
OPC	Ordinary Portland Cement
P	Vapour pressure (kPa)
P_0	Saturation vapour pressure (kPa)
P_{0sa}	Vapour pressure of air from equation 2-21 (kPa)
P_{0so}	Vapour pressure at concrete surface from equation 2-21 (kPa)
p_c	Volume fraction of capillary pores (%)
PFA	Pulverized fuel ash
p_g	Volume fraction of gel pores (%)
PRH	Pore relative humidity (%)
Q	Mass transport rate (g/m^2s)
R	Universal gas constant (8.3143 joule/mole.Kelvin)
r	Radius of meniscus formed in the capillary (m)
R_c	Volume fraction of unhydrated cement (%)

R_{c+g}	Volume fraction of the gel plus the cement (%)
R_g	Volume fraction of the gel (%)
R_h	Volume fraction of hydration products (%)
RH	Ambient relative humidity (%)
RH_{ave}	Weighted average relative humidity inside the environmental chambers (%)
RH_i	The i^{th} relative humidity measurement, used when calculating the weighted average relative humidity inside the environmental chambers (%)
R_s	Volume fraction of the solids in the paste (%)
t	Drying time (days)
T	Temperature (Kelvin or °C)
t_a	Additional curing time (days)
T_{ave}	Weighted average temepratüre inside the environmental chambers (°C)
t_e	Effective curing time (days)
t_i	The i^{th} time interval, used when calculating the weighted average conditions inside the environmental chambers
T_i	The i^{th} temperature measurement, used when calculating the weighted average temperature inside the environmental chambers (°C)
t_{in}	Initial period of wet curing (days)
t_{total}	Total period of time for which the weighted average conditions in the environmental chambers are calculated
V	Volume of the cement paste (m^3)
v	Wind velocity (kph)
V_c	The specific volume of anhydrous cement (0.32 cm^3/g)
w	Water:binder ratio of a concrete / mortar / HCP mix
W_i	Weight loss after i days of exposure (grams of moisture)
$w_n:c$	Chemically bound water content

1. INTRODUCTION

Concrete can, like any other building material, undergo deterioration and a consequent loss of quality and durability. A very important aspect of reinforced concrete durability is its ability to resist agents that would cause the steel reinforcement to corrode.

Steel in concrete is protected against corrosion by the high alkalinity of the material. The passivity of the steel is destroyed when the alkaline components become carbonated or in the presence of aggressive ions such as chloride. Together with the depassivation of the steel, sufficient moisture and oxygen have to be present for corrosion to take place.

The part of concrete protecting the reinforcement is the outer skin of the concrete, or covercrete. The pore structure of the covercrete plays a significant role in the ability of the structure to resist the ingress of aggressive agents. It is influenced by factors such as water:cement ratio, cement composition and the degree of cement hydration. In the context of this study, the potential durability of concrete can therefore be defined as the properties of the covercrete influencing the penetration and transportation of moisture, gases and chloride ions to the reinforcing steel, i.e. porosity, permeability and diffusivity.

Moisture in newly cast concrete governs hydration processes and the development of important durability related properties. Since environmental factors such as temperature, relative humidity and wind speed influence the evaporation of moisture, they play a role in moisture changes of the covercrete. The environment should therefore have a direct influence on the potential durability of a concrete structure.

Curing of concrete provides an artificial "ideal" environment at early ages, when the concrete is most vulnerable. It supplies sufficient moisture for the microstructure of the covercrete to develop. Previous studies [Ballim, 1993; Ho et al, 1989; Grube and Lawrence, 1984] showed that the potential durability of concrete is sensitive to wet curing.

When curing is neglected or not properly done, the natural environment is an important factor in the development of the covercrete properties. Since increasing emphasis is being placed worldwide on concrete durability, it is necessary to investigate the importance of environmental factors on moisture losses in concrete, at the end of the curing period. Index tests have been developed at the Universities of Cape Town and the Witwatersrand that measure the potential durability of concrete. These tests provide indices for potential durability, from measurements of oxygen permeability, water sorptivity and chloride conductivity of concrete specimens [Bouwer, 1998; Alexander, 1997; Ballim, 1993]. They provide a means to assess the influence of different variables on the potential durability of concrete.

In this project, the three index tests are used to assess and rate the importance of temperature, relative humidity and wind speed on the potential durability of concrete. The concrete samples were subjected to different periods of wet curing, prior to exposure to the environmental conditions under investigation. In this way the significance of the period of wet curing could be assessed.

1.1. Objectives

The objectives of the project are:

- To conduct careful characterisation work with the durability index tests. The influences of different environmental conditions in terms of relative humidity, temperature and wind speed on index values are investigated. The purpose of this is to assess the environmental factors most critical in governing the development of the desirable properties of the covercrete, and to assess the sensitivity of the covercrete to these environmental factors.

- To examine the effect of different periods of wet curing, as countermeasure for the negative effects of the environmental factors.
- To achieve a better understanding of the drying processes in concrete.

1.2. Scope and limitations of the work

The aim of the project was to introduce the use of the durability index tests in the evaluation of environmental influences on concrete durability. The investigation was restricted to one type of cement and one source of aggregates. Concrete strength grades investigated were 20, 40 and 60 Mpa. All samples were exposed to the environment on one face only. In practice this would be representative of structural elements such as slabs.

The environmental conditions simulated included temperatures ranging from 20 to 35°C, relative humidities between 50% and 100% and a 5,6 m/s wind velocity. The investigation was thus limited to plain concrete, one type of sample and moderate environmental conditions.

1.3. Structure of the report

The report is structured as follows:

- Chapter 2 is a résumé of the background and present status of cement hydration and the drying process, the influence of concrete curing and developments in methods to assess potential durability.
- Chapter 3 gives details on the laboratory equipment, materials and the type and number of samples used and the environmental conditions simulated during this investigation.
- Chapter 4 describes the test methods used during the experimental phase.
- Chapter 5 discusses the behaviour of environments simulated.
- Chapter 6 consists of the results of moisture losses from samples in different controlled environments.

- Chapter 7 gives the findings of the durability index tests conducted.
- Chapter 8 consists of the discussions of the experimental results of Chapters 6 and 7. Three topics are covered:
  1. The sensitivity of the covercrete to different environmental factors.
  2. The influence of the wet curing stage.
  3. The relationship between initial moisture loss and the index test results.
- In Chapter 9 a theory is formulated for concrete drying and its influence on the microstructure of the cement paste. This theory is related to the durability indexes obtained during this investigation.
- Chapter 10 presents the conclusions and recommendations of this investigation.

2. LITERATURE REVIEW

This chapter is a review of literature dealing with concrete durability and the important role played by moisture at early ages. Topics covered are the properties of hardened cement paste and concrete, the zone accountable for reinforced concrete durability (covercrete) and the influence of wet curing on potential concrete durability. A large part of the chapter deals with the drying processes in HCP and concrete. Finally, the philosophy behind the index testing of concrete, as well as the commonly used tests used to define potential durability, is discussed.

2.1. Factors influencing concrete durability

In the context of this study, the potential durability of concrete can be defined as the properties of the covercrete influencing the penetration and transportation of moisture, gases and chloride ions to the reinforcing steel, i.e. porosity, permeability and diffusivity. These properties are affected by the characteristics of the hardened cement paste, the aggregate, the paste-aggregate interface, the mixing, placing and curing practices and finally the environmental conditions.

2.1.1. Cement hydration

The chemical reaction between cement and water, transforming the compounds in cement into hardened cement paste (HCP), is called hydration. During this reaction the individual cement particles are bound together, producing a material with potentially good strength and durability properties [Ballim, 1991]. The important constituents in clinker involved in the hydration process are [Soroka, 1979]:

- tricalcium silicate or alite ($3CaO{\cdot}SiO_2$)
- dicalcium silicate or belite ($2CaO{\cdot}SiO_2$)
- tricalcium aluminate ($3CaO{\cdot}Al_2O_3$)

- tetracalcium aluminoferrite or celite ($4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$)

In cement chemistry it is usual to describe an oxide with a single letter, i.e.

- $CaO = C$
- $SiO_2 = S$
- $Al_2O_3 = A$
- $Fe_2O_3 = F$
- $H_2O = H$

Accordingly, alite is abbreviated as C_3S, belite as C_2S, tricalcium aluminate as C_3A and celite as C_4AF. The hydration of the C_3S and the C_2S produces a porous solid which may be defined as a rigid gel, called calcium silicate hydrate, or CSH gel [Soroka, 1979]. These reactions can be approximated by the following equations:

$$2C_3S + 6H \rightarrow C_3S_2H_3 + 3CH \qquad (2\text{-}1)$$

$$2C_2S + 4H \rightarrow C_3S_2H_3 + CH \qquad (2\text{-}2)$$

Since C_3S and C_2S make up about 90% of the cement [Soroka, 1979], the set cement consists mainly of their hydration products, and to a large extent determine the properties of the HCP. The CH (calcium hydroxide) makes the cement paste highly alkaline, with a pH of 12,5, which initially provides protection to steel reinforcement against corrosion.

The C_3A reacts with water almost instantaneously [Soroka, 1979]. To delay this reaction an amount of gypsum ($CaSO_4{\cdot}H_2O$ or $C\overline{S}H$) is added to cement. The quantity used is dependent on the amount of C_3A and varies between 2,5 - 3,0% [Soroka, 1979]. The C_3A initially reacts with the gypsum to form ettringite ($C_3A{\cdot}3(C\overline{S}){\cdot}H_{32}$, where $\overline{S}$ = sulphurtrioxide), until all the sulphate ions present in the solution (typically during the first 24 hours) are consumed. This reaction can be approximated by equation 2-3 [Mantel, 1992]:

$$C_3A + 3C\overline{S}H + 29H \rightarrow C_3A{\cdot}3(C\overline{S}){\cdot}H_{32} \qquad (2\text{-}3)$$

When the sulphate ions have been removed, further hydration of C_3A transforms the ettringite into a low-sulphate sulphoaluminate ($C_3A{\cdot}C\overline{S}{\cdot}H_{12}$) or into a hexagonal plate solid solution of $C_4A{\cdot}\overline{S}{\cdot}H_{12}$ and $C_4A{\cdot}H_{13}$ [Soroka, 1979]. At this stage, the limiting composition of the solid solution has been reached, and the remaining C_3A hydrates to produce $C_4A{\cdot}H_{19}$, approximated by equation 2-4:

$$C_3A + CH + 18H \rightarrow C_4A{\cdot}H_{19} \qquad (2\text{-}4)$$

The tetra-calcium aluminate hydrate (C_4AH_{19}) converts to a more stable tri-calcium aluminate hydrate (C_3AH_6), approximated by equation 2-5 [Soroka, 1979]:

$$3CaO{\cdot}Al_2O_3 + 6H_2O \rightarrow 3CaO{\cdot}Al_2O_3{\cdot}6H_2O \qquad (2\text{-}5)$$

In the early stages the celite (C_4AF) reacts with gypsum to form needle-like crystals of a solid solution consisting of high-sulphate sulphoaluminate and sulphoferrite [Soroka, 1979]. The reaction may be represented by the following equation:

$$C_4AF + C\overline{S}H_2 + CH \rightarrow C_3(A,F){\cdot}3(C\overline{S}){\cdot}aq \qquad (2\text{-}6)$$

With further hydration the solid solution converts into a low-sulphate aluminoferrite solid solution $C_3(A,F)C\overline{S}{\cdot}aq$ and/or into a solid solution phase in which sulphate ions are replaced by hydroxide ions $C_3(A,F)C(\overline{S},H){\cdot}aq$ [Soroka, 1979].

The impermeability of HCP is dependent on the completeness of the hydration process. According to Powers [1947] the volume of the cement gel is 2,2 times that of the unhydrated cement. The pores in the fresh cement paste are filled with hydration products, reducing the pore sizes and also the degree of interconnection between pores [Ballim, 1991]. The degree of impermeability of the HCP determines the rate at which aggressive agents can enter and diffuse through the material, increasing its durability properties.

To achieve a state of full hydration in HCP, all unhydrated cement particles must have access to water. This becomes increasingly difficult as the hydration process proceeds. The hydration products fill empty spaces and block the access paths of water to the unhydrated areas [Ballim, 1991]. Dense layers of CSH form around the cement grains and further hydration becomes dependent on the diffusion of water through these layers [Soroka, 1979]. The rate of diffusion depends on the thickness of the CSH layers and practically ceases when the thickness of a layer reaches 25μm. Accordingly, unhydrated cores are always left for cement grains with diameters greater than 50μm [Soroka, 1979].

Complete hydration is almost impossible to achieve, since a small part of cement remains unhydrated for long periods of time. Another effect takes place at w:c ratios smaller than approximately 0,42 [Ballim, 1991]. The hydration process requires more water than is readily available at such ratios. The cement paste 'dehydrates' itself in localised areas (self-desiccation) and a larger part of the cement remains unhydrated. Curing has very little influence in this case.

As a result of these factors, it is more appropriate to refer to the 'required' degree of hydration, rather than full hydration. This limit is reached by achieving the service requirements the concrete was designed for.

2.1.1.1. Degree of hydration

Water in HCP can be divided into three categories [Soroka, 1979]:

- Water that is combined in the hydration products, or chemically bound water, also called 'non-evaporable' water.
- Adsorbed water, bound by surface forces on the gel particles, or 'gel water'.
- Capillary water, not bound and free to evaporate.

The degree of hydration can be defined as the extent to which the constituents of the clinker have reacted with water to produce the hydration products of equations 2-1 to 2-4. At a stage of full hydration, no unhydrated cement will be left. The amount of chemically bound water can be used to describe the degree of hydration.

The amount of chemically bound water is related to the w:c ratio, the age of the HCP and the cement composition. Assuming that unhydrated cement grains will always have access to water and will continue to hydrate until 100% hydration is reached, the relation between the chemically bound water and the potential cement composition is given in equation 2-7 [Soroka, 1979]:

$$w_n{:}c = a_1(C_3S) + a_2(C_2S) + a_3(C_3A) + a_4(C_4AF) \qquad \text{(2-7)}$$

where c is the cement content, w_n is the amount of chemically bound water and C_3S, C_2S, C_3A and C_4AF are the fractional contents of alite, belite, tricalcium aluminate and celite respectively. The parameters a_i give the amount of water bound to each of the components relative to its weight and are given in Table 2-1.

Table 2-1: The coefficients a_i of equation 2-7 [Copeland et al, 1960]

a_i	**w:c ratio**				
	0,4	**0,4**	**0,6**	**0,8**	**0,4**
	1 year	**6,5 years**			**13 years**
a_1	0,228	0,234	0,238	0,234	0,230
a_2	0,168	0,178	0,198	0,197	0,196
a_3	0,429	0,504	0,477	0,509	0,522
a_4	0,132	0,158	0,142	0,184	0,109

As an example, the Riebeek West Portland cement used for this project contains typically 51,7% alite, 20,5% belite, 4,8% tricalcium aluminate and 10,3% celite [Streicher, 1996]. Using equation 2-7, the w_n:c ratio of this cement is approximately 0,20 after 13 years of constant exposure to water. A value of 23% combined water to weight of cement is generally assumed to be valid for well matured HCP of Portland cement and is taken as a value achieved for 100% cement hydration [Soroka, 1979].

2.1.1.2. The effect of w:c ratio on the degree of hydration

Experimental data relating degree of hydration (in terms of combined water to weight of cement, or w_n:c ratio) to w:c ratio, is given in Figure 2-1 [Soroka, 1979]. It can be seen that the degree of hydration for different w:c ratios is almost the same at early stages, but decreases at later stages. The lower the w:c ratio, the earlier the decrease in rate of hydration, which may be attributed to the decrease in available space the lower the w:c ratio, as well as the effect of self-desiccation. Soroka does not indicate the limits of hydration achieved for the different w:c ratios, after extended periods of time. As a result, the degree of hydration that can be achieved for different w:c ratios, is not clear from this figure.

The lines of Figure 2-1 can be approximated with empirical formulae, to provide estimates for the degree of hydration, as a function of curing time and w:c ratio. This is done in Chapter 9, where a theory for concrete drying is formulated. However, for a more exact model of the degree of hydration, factors such as the fineness of the cement, its composition and the curing temperature will have to be taken into consideration.

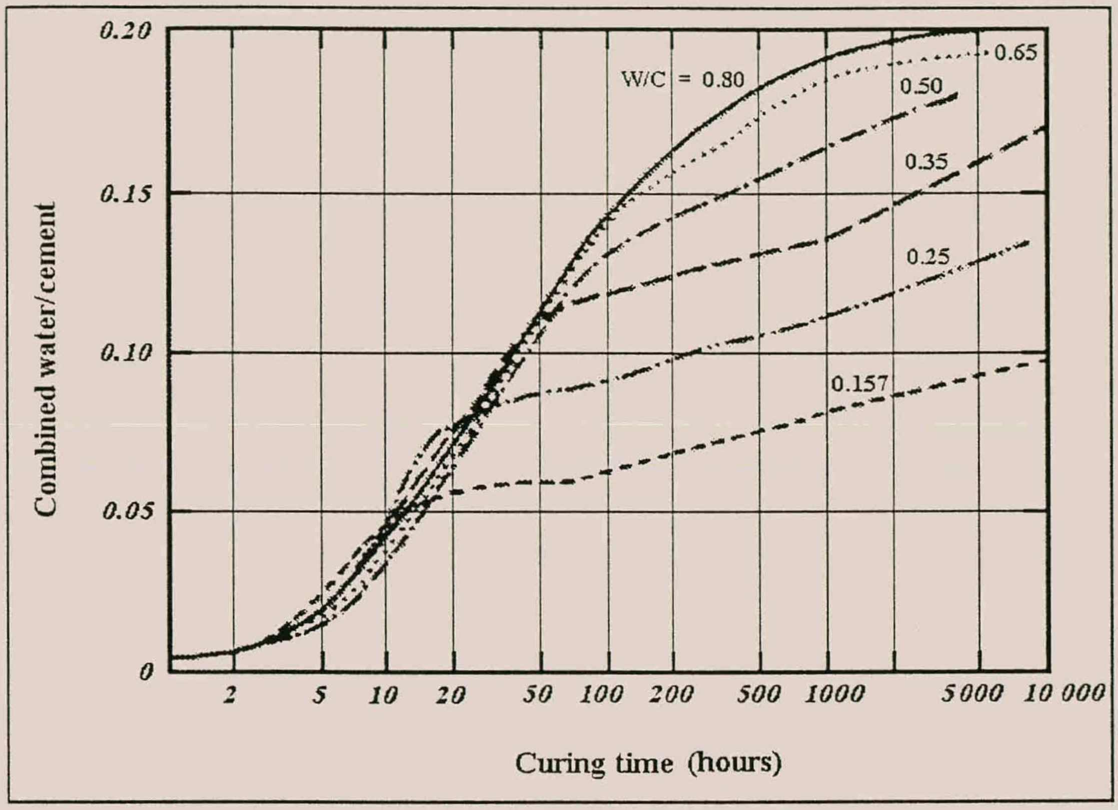

Figure 2-1: Effect of w:c ratio on the hydration of Portland cement [Soroka, 1979]

2.1.1.3. The effect of temperature on degree of hydration

Elevated temperatures influence cement hydration by accelerating the process, provided the rise in temperature does not cause drying of the paste. This only happens at early ages, as is illustrated in Figure 2-2, and does not influence the total degree of hydration achieved. The combined effect of increased evaporation of available moisture and increased rate of hydration is discussed in Chapter 8.

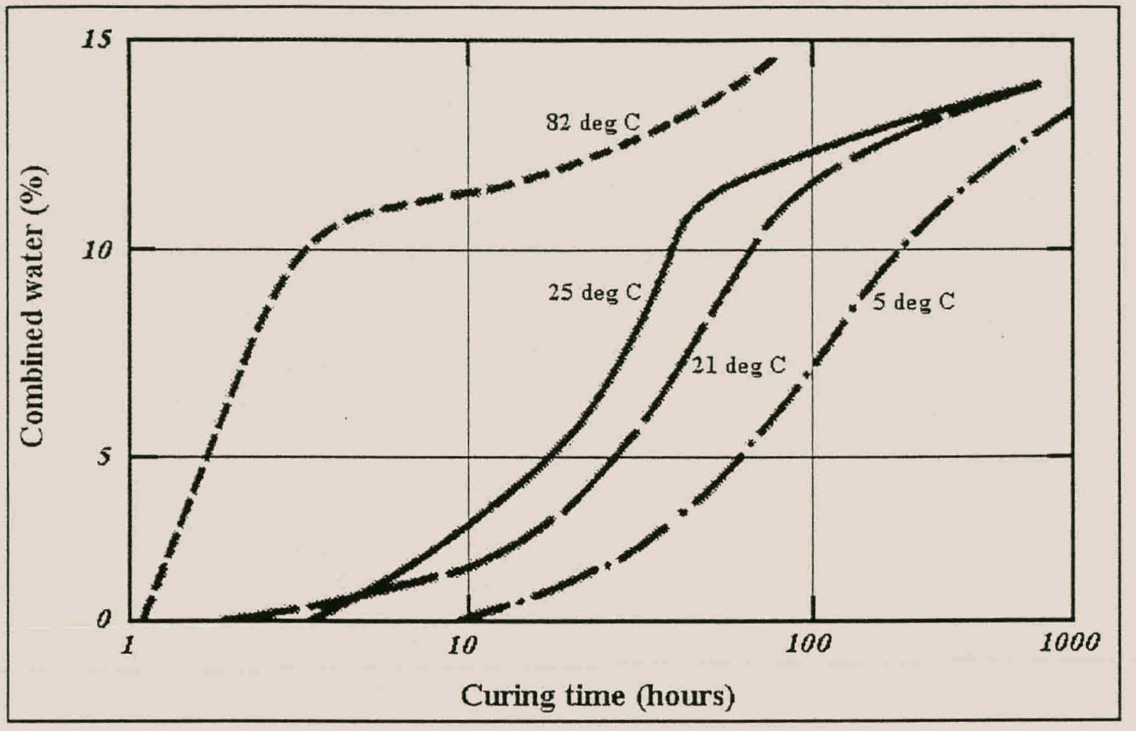

Figure 2-2: Effect of temperature on the degree of hydration as a function of curing time [Soroka, 1979]

2.1.2. Porosity of hardened cement paste

HCP is composed of the hydration products, unhydrated cement grains and capillaries. The cement gel has a characteristic porosity of 28% (called gel porosity), and since hydrated cement consists mainly of the hydration products of C_2S and C_3S (i.e. cement gel), this implies that HCP has a porosity of at least 28% (even at full hydration). However, total porosity (gel + capillary porosity) can be as much as 50% for average quality paste, where a large part of the HCP consists of capillary pores [Powers, 1978]. The amount of capillaries is determined by the w:c ratio and the degree of hydration of the paste [Soroka, 1979]. At a w:c ratio of 0,40 the bulk volume of the cement gel will be sufficient to fill all the empty spaces and produce a cement paste free of capillary pores. Higher w:c ratios will result in greater volumes of capillary pores, almost continuously distributed through the HCP. At w:c ratios lower than 0,70, and with sufficient wet curing, these capillaries can become isolated, but above this ratio no amount of wet curing will be sufficient to isolate the capillaries [Verbeck, 1978]. The process by which the interconnection of capillary pores reduces due to continued hydration, is called segmentation [Hearn et al, 1994].

The pores in HCP can be classified in terms of size, the role water plays and the paste properties affected [Mindess and Young, 1988]. Based on these criteria, the distinctions between macro-pores, capillary pores and gel pores are made in Table 2-2. As will be seen in section 2.3.3.1, the pore size distribution of the HCP plays a significant role during drying processes and the consequent development of the cement paste properties.

Table 2-2: Classification of pore sizes in hydrated cement paste after Mindess and Young [1988]

Desig-nation	Diameter (nm)	Description	Role of water	Paste properties affected
Macro-pores	$1,0 \times 10^6$ – $1,5 \times 10^3$	Large, spherical voids	Behaves as bulk water	Strength, permeability
Capillary pores	$1,5 \times 10^3$ - $0,05 \times 10^3$	Large capillaries	Behaves as bulk water	Strength, permeability
	50 - 10	Medium capillaries. Capillary cavity. Inter gel-particle pores.	Moderate surface tension forces generated	Strength, permeability, shrinkage at high humidities
Gel pores	10 - 2,5	Small (gel) pores.	Strong surface tension forces generated.	Shrinkage to 50% RH
	2,5 - 0.5	Micropores. Gel pores. Inter-crystallite pores.	Strongly adsorbed water, no menisci formed. Structural water	Shrinkage, creep
	< c. 0,5	Micropores "interlayer" (interlayer space). Intra-crystallite pores.	Involved in bonding	Shrinkage, creep

2.1.2.1. Calculation of cement paste properties

The cement paste properties can be estimated if the following assumptions are made [Soroka, 1979]:

1. The volume of the cement gel is 2,2 times the volume of the anhydrous cement, and the gel has a characteristic porosity of 28%.
2. At w:c ratios higher than 0,40, the volume of the cement paste is equal to the sum of the volumes of the anhydrous cement and the mixing water.
3. The specific volume of anhydrous cement (V_c) is 0,32 cm^3/g.

The amount of capillaries at any time is dependent on the volume change and is a function of the w:c ratio and degree of hydration.

From the second assumption, the volume of the paste is:

$$V = CV_c + wC \tag{2-8}$$

where V = volume of the paste

C = weight of the cement

V_c = specific volume of cement (0,32 cm^3/g)

w = w:c ratio (the specific volume of water is 1 cm^3/g)

For a given degree of hydration, α, the volume fraction of unhydrated cement, R_c, in the paste is given by:

$$R_c = \frac{CV_c(1-\alpha)}{CV_c + wC}$$

or

$$R_c = \frac{V_c(1-\alpha)}{V_c + w}$$

with V_c = 0,32

$$R_c = \frac{0{,}32(1-\alpha)}{0{,}32 + w} \tag{2-9}$$

According to the first assumption the gel volume is equal to 2,2 times the volume of the reacting cement and the volume fraction of solids in the HCP is 72% of the volume of the gel (for a porosity of 28%. The volume fraction of the solids in the paste is the sum of the hydration products and the unhydrated cement, hence the total fraction of solids (R_s) is given by:

$$R_s = \frac{0{,}32(1-\alpha)}{0{,}32+w} + \frac{0{,}72 \cdot 2{,}2 \cdot 0{,}32\alpha}{0{,}32+w}$$

or

$$R_s = \frac{0{,}32+0{,}187\alpha}{0{,}32+w} \tag{2-10}$$

Similarly, the volume fraction of the gel plus the cement, R_{c+g}, is given by

$$R_{c+g} = \frac{0{,}32(1-\alpha)}{0{,}32+w} + \frac{2{,}2 \cdot 0{,}32\alpha}{0{,}32+w}$$

or

$$R_{c+g} = \frac{0{,}32+0{,}384\alpha}{0{,}32+w} \tag{2-11}$$

From these equations the volume fractions of the gel (R_g), hydration products (R_h), gel pores (p_g) and the capillary pores (p_c) are given by equations 2-12 to 2-15:

$$R_g = R_{c+g} - R_c \tag{2-12}$$

$$R_h = R_s - R_c \tag{2-13}$$

$$p_g = R_{c+g} - R_s \tag{2-14}$$

$$p_c = 1 - R_{c+g} \tag{2-15}$$

The degree of hydration (α) can be estimated from Figures 2-1 and 2-2. Thus, with the w:c ratio and the degree of hydration known, the above equations give the volume fractions of the:

- unhydrated cement (R_c),
- solids (R_s),
- gel plus unhydrated cement ($R_{c+g,}$),
- gel (R_g),
- hydration products (R_h),
- gel pores (p_g), and
- capillary pores (p_c)

In Table 2-3 sample calculations are shown for w:c ratios of 0,40 and 0,70 and degrees of hydration* of 0, 50% and 100%. A volumetric diagram illustrates these results in Figure 2-3.

Table 2-3: Influence of w:c ratio and degree of hydration on the porosity of HCP

Component	**Relative volume (%)**					
	w:c ratio = 0,40			**w:c ratio = 0,70**		
	Degree of hydration (%)					
	0	**50**	**100**	**0**	**50**	**100**
Unhydrated cement	44,4	22,2	0	31,4	15,7	0
Gel	0	48,9	97,8	0	34,4	69,0
Capillary pores	55,6	28,9	2,2	68,6	49,9	31,0
Total	100	100	100	100	100	100
Gel pores *	0	13,7	27,4	0	9,6	19,3
Total porosity **	**55,6**	**42,6**	**29,6**	**68,6**	**59,8**	**50,3**

* Cement gel has a characteristic porosity of 28%.

** Total porosity = capillary pores + gel pores

* The degree of hydration can also be expressed as the percentage of full hydration achieved.

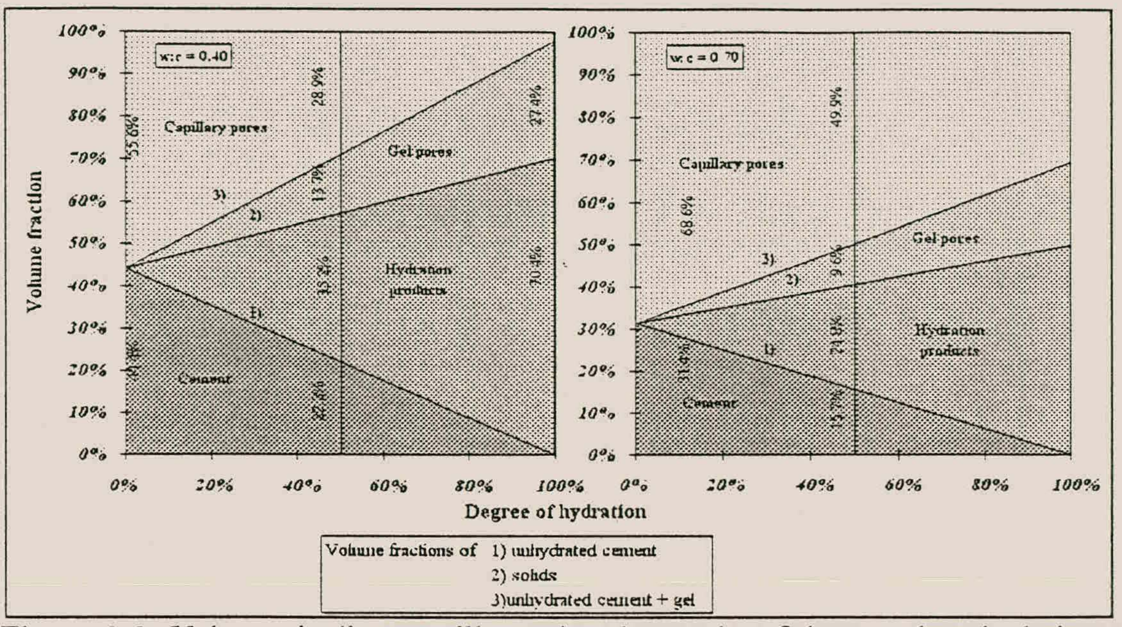

Figure 2-3: Volumetric diagram, illustrating the results of the sample calculations of Table 2-3 [Soroka, 1979]

2.1.3. Porosity of hardened concrete

Hardened concrete consists of HCP, aggregates and entrapped voids. The HCP is composed of cement gel, unhydrated cement grains and space not filled with cement gel (i.e. capillary pores), as discussed in the previous section. The cement gel has a porosity of 28%, while the porosity of the aggregate is typically between 1% and 5% [Oberholster, 1986]. Therefore the pores in concrete consist of gel pores and capillary pores in the cement paste, entrapped pores, entrained pores (where an air-entraining agent has been used) and pores in the aggregate. The resulting porosity of concrete ranges between 7% and 15% for very good and average quality concretes respectively [Oberholster, 1986].

The porosity of concrete influences diffusion rates of gases and fluids through the solid matrix and is therefore important, from a durability point of view. Following are detailed discussions of these properties and moisture diffusion through hardened concrete, as well as a discussion of the zone of concrete accountable for providing cover to reinforcing steel (covercrete).

2.1.3.1. Permeability of hardened concrete

The rate of mass transfer through a porous solid and its mechanical properties are influenced by its pore system [Hearn et al, 1994]. Although hardened concrete contains a significant amount of pores, they are very small and rather isolated (see section 2.1.2), restricting its permeability to water.

Apart from the influence of the porosity of the cement paste, the permeability of hardened concrete is also dependent on the aggregate content and properties, the nature of the paste-aggregate interface and macro-effects, such as bleeding channels (see section 2.1.3.2).

2.1.3.1.1. Permeability of HCP

In HCP, the small size of gel pores causes a great affinity of water molecules to the gel surfaces. Combined with the fact that these pores are only one order of magnitude larger than the water molecules, the movement of water in gel pores contributes little to the total permeability. Thus the larger capillary pores (10 to 500 nm) are the primary source of the permeability of HCP. The extent to which the capillary porosity influences the coefficient of water permeability*, depends on the w:c ratio of the paste and is illustrated in Figure 2-4.

As mentioned in section 2.1.2.1, the degree of hydration also influences the porosity, and therefore permeability, of HCP. The reduction of permeability of cement pastes with continued hydration, for a w:c ratio of 0,60, is given in Table 2-4 [Powers, 1954].

* The coefficient of permeability is a defined by the Darcy equation for permeation (see section 2.1.3.2.4).

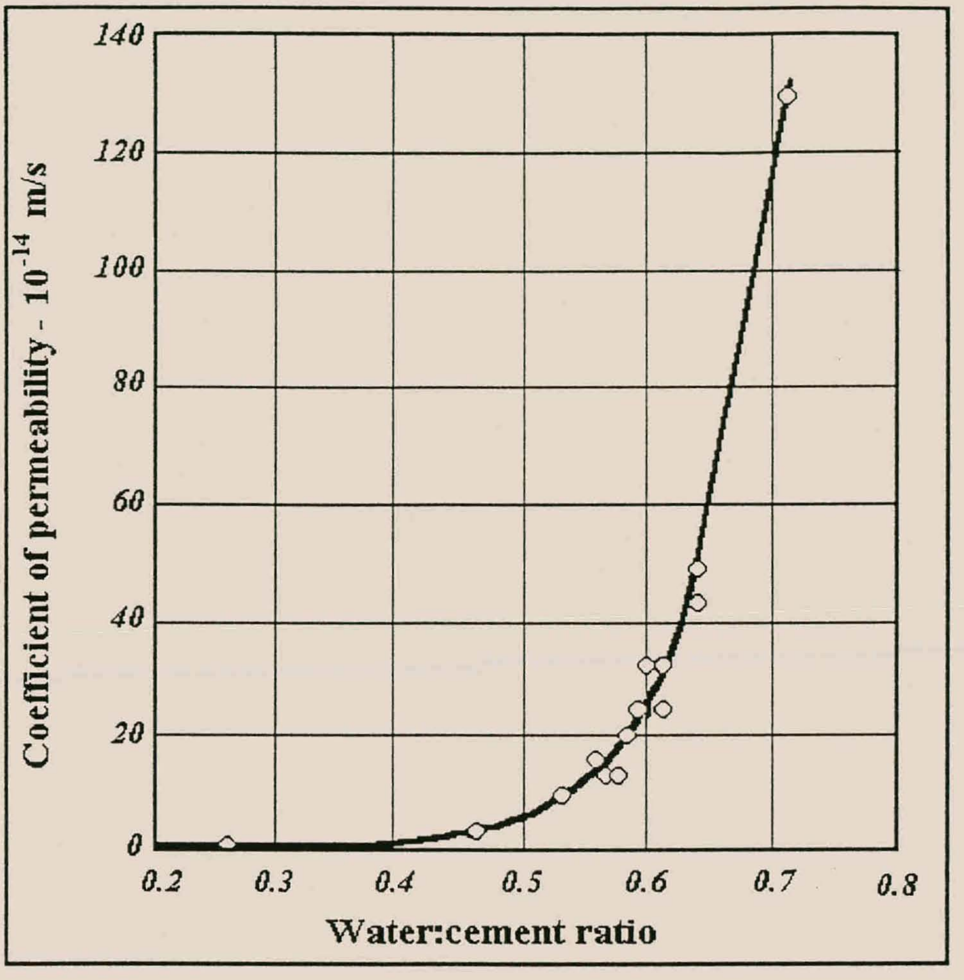

Figure 2-4: Relationship between water permeability and w:c ratio for well matured cement pastes [Powers, 1958]

Table 2-4: The reduction of permeability of cement pastes with continued hydration (w:c ratio = 0,60) [Powers, 1954]

Age (days)	Coefficient of permeability, K (m/s)
Fresh	2×10^{-6}
5	2×10^{-10}
6	2×10^{-10}
8	2×10^{-11}
13	2×10^{-12}
24	2×10^{-12}
Ultimate	20×10^{-14} (calculated)

2.1.3.1.2. Permeability of the aggregate

The porosity of aggregates is usually under 3% and seldom more than 10% [Hearn et al, 1994]. However, their permeability may in some cases approximate that of high w:c ratio cement pastes [Powers, 1958] (Table 2-5). The relatively high permeability / porosity ratio in aggregates, relative to cement, results from:

- A high degree of continuity in aggregate pores, due to jointing and fissures.
- Coarser pore distributions in aggregates.

Table 2-5: Comparison between permeabilities of rocks and cement pastes [Powers, 1958]

Type of rock	Coefficient of permeability (m/s)	W:c ratio of mature pastes of the same permeability
Dense trap	$2{,}47 \times 10^{-14}$	0,38
Quartz diorite	$8{,}24 \times 10^{-14}$	0,42
Marble	$2{,}39 \times 10^{-13}$	0,48
Marble	$5{,}77 \times 10^{-12}$	0,66
Granite	$5{,}35 \times 10^{-11}$	0,70
Sandstone	$1{,}23 \times 10^{-10}$	0,71

2.1.3.1.3. Permeability of the cement paste-aggregate interface

During mixing of concrete, aggregates are surrounded by thin films of water. This leads effectively to higher w:c ratios of a thin layer of cement around the aggregates (approximately 20 μm). This zone, which is more porous, can be increased by trapped bleed water. Also, at early stages calcium hydroxide and ettringite contribute to the porosity of this zone. There is thus in general a weak, porous layer surrounding the aggregate.

This interface is thus generally more permeable than either the cement paste or the aggregate, and moisture flow is channelled along these paths, rather than through the aggregate itself [Hearn et al, 1994]. Therefore, the inclusion of aggregates effectively increases the permeability of HCP.

2.1.3.1.4. Permeability caused by the manufacturing of concrete

Voids other than gel, capillary and aggregate pores also occur to a greater or lesser extent, depending on the quality of the mix design and manufacturing process. These are bleeding channels, pockets and cavities under aggregates and reinforcing bars, as well as honeycombing (large, irregular voids due to poor compaction).

The formation of bleeding channels creates continuous flow paths. Also, as the upward movement of the bleeding water is obstructed by aggregates, zones of low density occur below the aggregates. Both of these effects increases the permeability of the concrete, and the latter is the primary reason for differences in permeability of cement paste, mortar and concrete.

Plastic settlement, plastic shrinkage and thermal contraction may cause cracks in fresh concrete, whereas, in the long term, cracks may be caused by reversible and irreversible drying shrinkage, sulphate attack, alkali-aggregate reaction and structural movement [Oberholster, 1986]. Microcracks are usually larger than most capillary cavities and generally provide continuous flow paths through the cement matrix [Hearn et al, 1994], increasing the permeability of the concrete.

2.1.3.2. Moisture diffusion in hardened concrete

Moisture diffusion in concrete is influenced by cracking and properties of the cement paste, as well as moisture content* and boundary conditions [Hearn et al,

* Moisture content can be defined as the degree of saturation of the pores, and can be described in terms of pore (or internal) relative humidity. Relative humidity is defined as the vapour pressure over a liquid (P) to the saturated vapour pressure of the liquid, usually defined as a percentage, in other words (P/P_0)x100. Saturation vapour pressure of a liquid is defined as the pressure at which

1994]. As the pore relative humidity (PRH) drops from 90% to 60%, the diffusion coefficient** decreases sharply from 2,2 x 10^{-6} to 5,5 x 10^{-11} m^2/s [Bazant and Najjar, 1971]. Below 60% PRH, it appears to be approximately constant. This implies that moisture diffuses more rapidly under saturated conditions than under dry conditions.

As mentioned before, moisture in HCP is divided into non-evaporable and evaporable water, of which the latter is significant during moisture diffusion processes. Evaporable water can be divided into adsorbed and interlayer water, as well as mobile (capillary condensed) water [Hearn et al, 1994]. Changes in boundary conditions, such as temperature, pressure or chemical potential, affects the state of water retained in HCP. The adjustments made to such changes to recover equilibrium is controlled through humidity flux, which includes adsorption, surface diffusion, vapour diffusion and bulk flow [Hearn et al, 1994]. These will be discussed in the following sections.

2.1.3.2.1. Adsorption

Adsorption is the process by which water molecules are retained by attraction forces to the solid at different energy levels. This occurs at all pore relative humidities, but mainly below 45% [Powers, 1960]. As menisci cannot exist below this pore relative humidity (see section 2.3.3.1.1), the water in concrete under such conditions is all adsorbed water. At low relative humidities, mass transfer of water vapour occurs by molecular migration, rather than coherent flow [Mills, 1985].

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the liquid and its vapour are at equilibrium, meaning that the amounts of molecules evaporating and returning to the liquid are the same. As soon as the vapour pressure over a liquid drops below this value, evaporation takes place and the amount of liquid reduces.

** Defined by Fick's first law of diffusion for steady state conditions (see section 2.1.3.2.3).

2.1.3.2.2. Surface diffusion

Water vapour molecules are highly adsorbing because of their polarity and the hydrophilic nature of HCP. The adsorbed molecules, no longer in a gaseous state, are so strongly attracted to the bounding surface that they have a relative density of 0,9 and assume the characteristics of a fluid of very high viscosity [Powers, 1960]. Under these circumstances, loosely bound top molecular layers of condensate slide over underlying layers, wetting bounding surfaces and thus causing mass transfer. Higher relative humidities will result in the build-up of adsorbate layers, until capillaries begin to fill and vapour diffusion and bulk flow become the governing transport mechanisms.

2.1.3.2.3. Vapour diffusion

The diffusion of vapour is important, since molecules can be transferred without movement of condensed water masses. Vapour diffusion of water occurs according to Fick's first law:

$$Q = D_p\left(\frac{dp}{dx}\right) \quad (2\text{-}16)$$

where Q = mass transport rate (g/m^2s)

D_p = diffusion coefficient (m^2/s)

dp/dx = vapour pressure potential (m/m)

Rose [1965] describes this process as a "short circuit" effect, caused by the continuous film of moisture in partially saturated samples of HCP, which provides rapid moisture transfer without coherent flow (Figure 2-5). This concept can be visualised by considering a situation where the atmosphere on the upstream side, the menisci in pores of the solid and the atmosphere on the downstream side are in equilibrium. This implies that the amount of water molecules evaporating from the surface of the meniscus is exactly equal to the amount condensing onto the meniscus. With a change in the relative difference between vapour pressures on the up- and downstream sides, the hydrostatic tension of the condensed water reduces and rapidly creates disequilibrium, with the result that water molecules are ejected in order to equalise hydraulic tension.

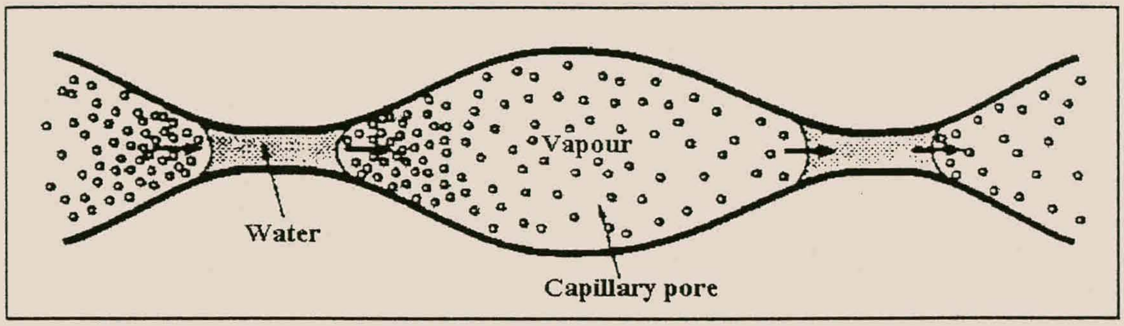


Figure 2-5: "Short circuit" mass transfer by vapour diffusion [Hearn et al, 1994]

2.1.3.2.4. Bulk flow

Bulk flow describes the movement of a liquid through an unsaturated or saturated matrix, or both [Hearn et al, 1994]. In an unsaturated material with one end exposed to water and the other to the atmosphere, the bulk of the moisture flux will be transmitted by capillary tension. To transfer water mass, capillary movement relies on the difference in pressure over the up- and downstream surfaces of the menisci. The curvature of the meniscus is a function of the vapour pressure and becomes zero at saturated conditions.

At the saturation stage, a pressure head is required to drive water through the matrix and Darcy flow governs. This relation is given as:

$$\left(\frac{\partial m}{\partial t}\right) = \frac{-K}{g}\left(\frac{\partial P}{\partial z}\right) \qquad (2\text{-}17)$$

where $\partial m/\partial t$ = rate of flow (m^2/s)

$\partial P/\partial z$ = the pressure gradient in the direction of flow

K = coefficient of permeability (m/s)

g = acceleration due to gravity

2.1.3.2.5. Summary of moisture diffusion in hardened concrete

Three stages of moisture transportation in concrete occur [Hearn et al, 1994]:

- Below pore relative humidities of 45%, no meniscus is formed and moisture movement is controlled by adsorption and surface diffusion.
- Between pore relative humidities of 45% and close to saturation, moisture is transferred through vapour diffusion and capillary tension.
- In saturated and near-saturated material, moisture transfer is mainly due to laminar flow, controlled by viscosity and Darcy's law.

Flow in unsaturated concrete may be supported by all the above mechanisms [Hearn et al, 1994]. Numerical analysis of moisture flow is further complicated by the complexity of the pore structure, its variation with mix proportions, curing and conditioning, as well as variation with time due to continued hydration.

2.1.3.3. Covercrete

The durability of reinforced concrete structures depends largely on the properties of the outer 'skin' of concrete, or covercrete. Good quality concrete, sufficient curing, good compaction and sufficient cover to the reinforcing steel are important considerations for concrete durability. The properties of the covercrete are also dependent on factors such as water:binder ratio, binder content and binder type [Ballim, 1991].

Covercrete is generally defines as the outer regions of the concrete, which covers the reinforcing steel [Ballim, 1991]. The primary function of the covercrete is to act as a barrier between the environment and the steel reinforcement. Any aggressive agent has to penetrate a concrete structure from the outside. Therefore durability is not a bulk property of concrete (like strength), but rather a surface property, determined by the composition and properties of the surface layers of the concrete providing cover to the steel reinforcement.

The covercrete consists of three layers [Kreijer, 1984]:

- A cement layer, approximately 0,1 mm thick.
- A mortar skin, approximately 5 mm thick.
- A concrete skin, approximately 30 mm thick (depending on the thickness of cover to the steel reinforcement).

These layers are a result of sedimentation and segregation due to the effects of gravity, compacting methods and movement of water in and out of the concrete [Kreijer, 1984].

Therefore, the concrete properties change with depth into the covercrete. Gradients exist in w:c ratios, aggregate:cement-ratios and porosity. These variations cause differential strength, deformability and drying and thermal shrinkage [Kreijer, 1984]. The porosity of the covercrete results in increased rates of wear, abrasion and ingress of aggressive agents.

In this project, the development of the covercrete properties as a function of w:c ratio, period of wet curing and environmental conditions is investigated.

2.2. Wet curing of concrete structures

When concrete is exposed to the environment, the covercrete is the first section to dry. In the case of structural members with a high exposed surface to volume ratio, such as thin slabs, the heartcrete could also be influenced by drying processes, affecting the strength of the member. However, in most structural members the exposed area:volume ratio is small enough to protect the heartcrete from rapid drying processes. The drying gradient in this zone is usually too small to force all the water to the exposed surface [Ballim, 1991]. In these cases the heartcrete reaches the required extent of hydration and develops the properties it was designed for.

The covercrete, on the other hand, is subjected to higher drying gradients and consequently gradients of porosity, due to factors such as relative humidity, temperature, wind speed, duration of exposure and depth from the exposed surface [Patel et al, 1988]. The zone affected by the external environment at relatively early ages, is called the *curing-affected zone* (CAZ) and has been estimated to be between 20 and 50 mm in depth.

Curing is usually defined as the process of maintaining a satisfactory moisture content and a favourable temperature in concrete in the period immediately following placement so that hydration may continue until the desired properties are developed to a sufficient degree to meet the requirements of service [Ballim, 1993]. Cather [1994] gives two other definitions for curing:

(a) materials science definition - 'curing is the creation of an environment in which hydration reactions can proceed to help fulfil the aim of producing concrete of adequately low porosity.'

(b) engineering definition - curing is adequate when the resulting concrete achieves the expected service performance.

The direct curing of structural elements with water is rarely practical, and more commonly the evaporation of water is prevented. It has been shown that concrete cured under water develops higher strengths than the same concretes that have been sealed to prevent moisture losses [Cather, 1994]. This is a result of self-desiccation and is caused by the consumption of pore water by hydration of the cement. The degree of self-desiccation is dependent on w:c ratio: the lower the w:c ratio the higher the degree of self-desiccation [Soroka, 1979].

2.2.1. The effect of curing on covercrete performance

Ballim [1993] did an investigation on the influence of wet curing on the potential durability of concrete. Cubes (100 mm) were cast, wet cured for different periods of time and left to dry at 23°C and 65% RH. Four of the six faces of the cubes were sealed, allowing uni-directional drying. After 28 days of drying, the oxygen permeability and water sorptivity of the specimens were tested. The following conclusions were made:

- Wet curing had a significant influence on the oxygen permeability indexes* of all the concretes investigated. Lack of curing could cause an increase of up to 50 times in this index.
- The extent of moist curing had a considerable effect on the water sorptivity index, although not quite as much as in the case of oxygen permeability.

In another study by Ho et al [1989], water sorptivity was used to determine the influence of wet curing on potential concrete durability. OPC and fly ash concrete samples were wet cured (covered in plastic for 24 hours after casting, and then placed inside a fog room) at 23°C for periods of 1, 3, 7, 28 and 91 days and results were compared to the sorptivity measured at 28 days. The water penetration testing involved subjecting one face of the specimen to continuous water spray at an air pressure of 0,5 kPa. The depths of water penetration were noted visually by splitting specimens at periods of 0,5, 2, 4, 8, 16 and 24 hours. The 28-day (cylinder) compressive strength of the concrete was 32 MPa. Typical results are shown in Figure 2-6.

* Ballim [1993] used the oxygen permeability and water sorptivity index tests also applied during the present investigation, which are described in section 2.5.2.

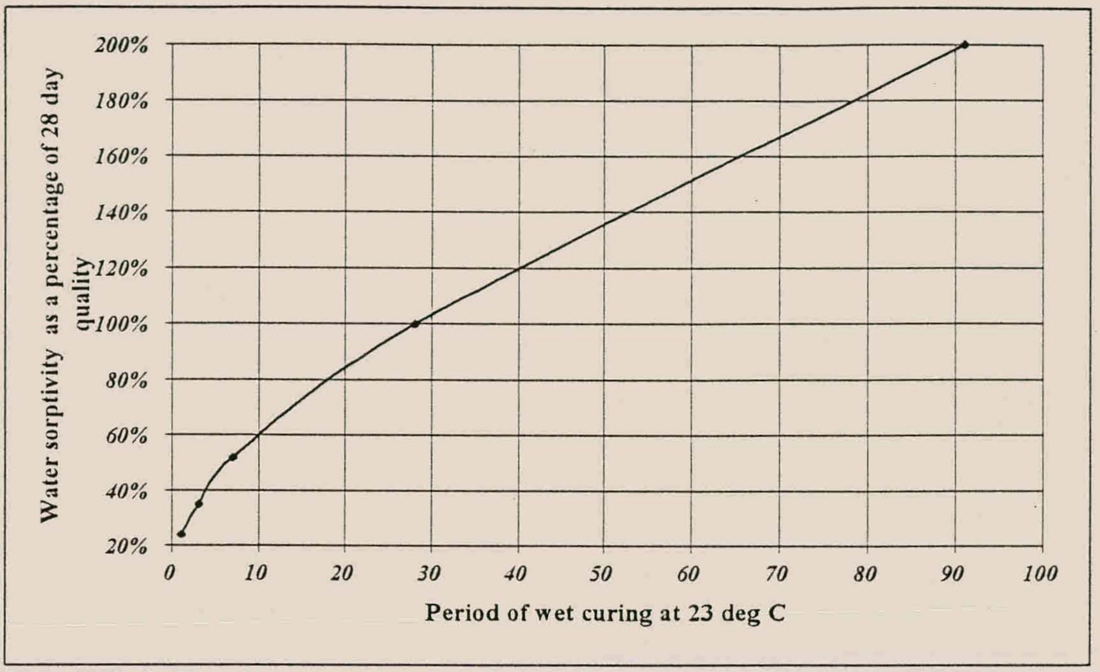


Figure 2-6: Results on water sorptivity from concretes wet cured for different periods of time [Ho et al, 1989]

These results indicate that concrete quality was doubled by increasing curing from 1 to 7 days, and quadrupled by extending curing to 28 days. After 91 days of wet curing, sorptivity results indicated a concrete of quality double that achieved after 28 days of wet curing.

Grube and Lawrence [1984] reported the initial results of a joint investigation on the permeability of concrete to oxygen. Large variations were found for the same mixes, suggesting the sensitivity of oxygen permeability to casting, small changes in mix design and degree of curing. Initial curing was found to be the most important. The oxygen permeability after 3 days of wet curing, compared to 1 day of wet curing, had decreased by five times (on average) and by nine times after 28 days of wet curing.

The w:c ratio had a lesser but still important effect. On average an increase of w:c ratio of 0,05 led to an increase in permeability of 1,6 times. Increasing the cement content from 240 kg/m^3 to 300 kg/m^3 led to an increase in permeability of 2,1 times for a w:c ratio of 0,70, mainly because of a higher water content in the cement paste.

2.2.2. The 80% relative humidity limit for concrete curing

There are views, particularly by UK researchers [Patel et al, 1988], that average ambient relative humidities of higher than 80% throughout the year would be sufficient and no curing should be necessary under such circumstances. This is a result of:

1. *The influence of relative humidity on evaporation of moisture from the covercrete.* Although there would be a difference between ambient relative humidity and pore relative humidity, these two are linked and depend on the difference between them and the microstructure of the concrete [Cather, 1994]. Drying under such humid conditions is slowed significantly, leading to longer periods of moisture retention in the covercrete and consequently higher degrees of hydration. This aspect is discussed in detail in section 2.3.3.1.1.
2. *The hydration reaction is very sensitive to adequate amounts of water.* It has been shown [Parrott, 1988] that the rate of cement hydration drops to 50% (compared to saturated conditions) at 90% PRH and to 32% at 80% PRH.

Powers [1947] investigated the influence of varying relative humidity on dry cement. At relative humidities less than 50% no change occurred and no hydration took place. At 70% the cement sample became somewhat lumpy and at 80% it formed a caked mass that could be broken up easily. At 89% the mass was harder and at 100% the sample became a solid cake of HCP. This indicates a drastic increase in cement hydration at relative humidities above 80%.

Powers concluded that the relative humidity within a concrete mass should be kept above 80% to achieve an appreciable continuation of hydration. At relative humidities lower than 80%, hydration effectively ceases. If concrete is allowed to dry out at an early age, the strength, permeability and durability will be impaired. Powers' results are summarised in Figure 2-7.

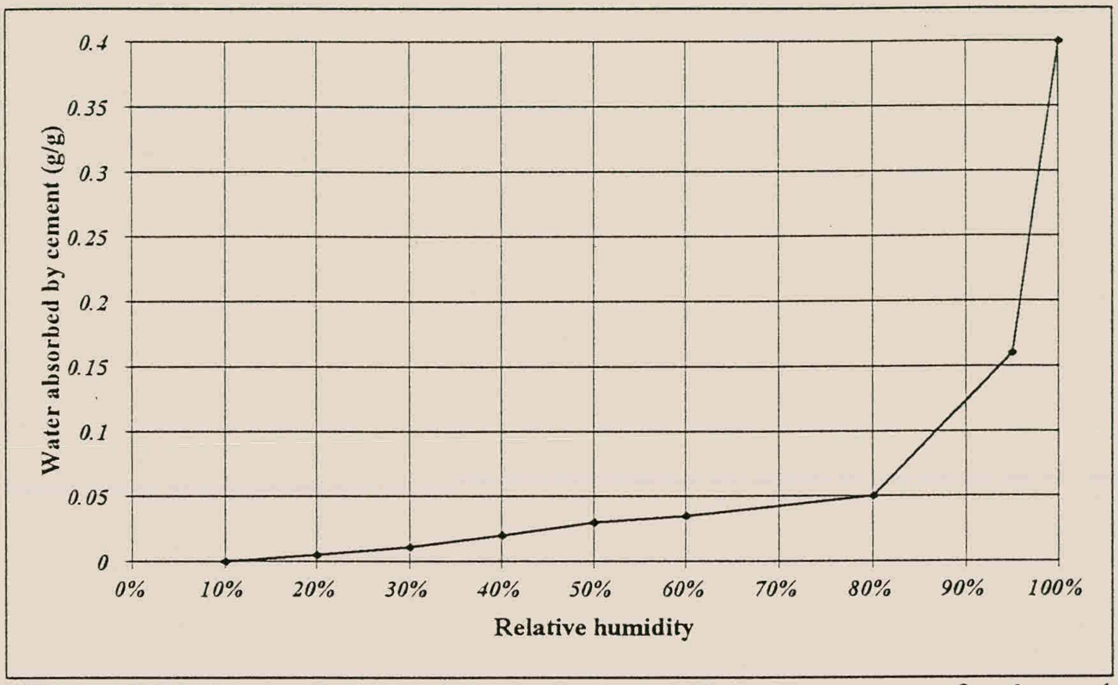


Figure 2-7: Water gained by dry cement exposed to water vapour for 6 months [Powers, 1947]

2.3. Drying processes of hardened concrete

The importance of sufficient moisture in the development of durability-related properties of concrete, especially at early ages, has been discussed in section 2.2. However, in many cases inadequate curing reduces the rate of hydration, which results in the coarsening of the pore structure of the cement paste matrix. The extent of the damage caused by different drying regimes is an important topic and is discussed in more detail in the next section.

2.3.1. Overview of the drying of concrete and HCP

When newly cast concrete is first exposed to the environment, i.e. ideally at the end of the curing period, an immediate humidity gradient is established between the saturated pores of the concrete and the surrounding environment. Water starts evaporating from the surface layers, and a humidity gradient is established inside the concrete.

The capillary sizes from which evaporation occur are dependent on the temperature and relative humidity of the surrounding concrete. Larger pores are emptied first and only later smaller pores subsequently [Soroka, 1979]. The humidity gradient in the concrete results in hydraulic tension forces and water molecules diffuse towards the exposed surface by the mechanisms discussed in sections 2.1.3.2.1 to 2.1.3.2.4 (adsorption, surface diffusion and vapour diffusion).

While the pore relative humidity and temperature governs the *pore sizes* from which evaporation can occur, these effects also determine the *rate of evaporation* of the pore water. In other words, capillaries also empty at faster or slower rates, depending on the severity of their neighbouring environment.

Wind speed might also have an influence on moisture loss from hardened concrete, since it affects the rate of evaporation of moisture. However, its influence would not be able to penetrate much deeper than the immediate concrete surface and it is not expected to have any significant influence. No literature could be found on this topic.

The rate of moisture loss is therefore dependent on:

- The severity of the surrounding environment, which determines which pore sizes lose water through evaporation, as well as the rate at which moisture is lost.
- An internal humidity gradient that causes hydraulic tension forces. The magnitude of these forces and the pore size distribution of the concrete determine the rate of diffusion of moisture from deeper regions in the concrete to exposed surfaces. As the internal relative humidity reduces, the transport mechanism changes from capillary action to vapour diffusion, then surface diffusion and finally molecular migration. Thus the forces required to

transport molecules to the surface increase and rate of moisture loss decreases with time.

2.3.2. Assessing the drying of concrete

Parrott [1988] classifies methods of moisture measurement in the following groups:

- Weight changes on specimens of particular shapes and sizes.
- Measurements of internal relative humidities.
- Weight changes corresponding to selected depths from exposed surfaces.

The most useful of these is the measuring of internal relative humidity of concrete specimens subjected to drying, since the pore relative humidity is a direct indicator of the amount of ongoing hydration at various depths inside a concrete sample. Parrott [1991] did much work in the field of concrete drying, including all three of the above methods. His work is of direct interest to this study and his findings will be reviewed in the following paragraphs, together with work of the same nature done by other researchers.

Parrott found that the initial weight losses of concrete specimens correlated broadly with the water absorption rate, carbonation depth and air permeability after extended exposure for a wide range of experimental conditions. The extent to which the above properties develop is a function of the initial rate at which moisture is lost: the greater the initial weight loss rate, the poorer the long-term performance in terms of durability.

2.3.2.1. Rate of weight loss during initial exposure as an indicator of covercrete performance

In Parrott's study, the effects of five w:c ratios, five exposure conditions, three periods of moist curing and four cements on the weight losses of 100 mm cubes were investigated. The details are given in Table 2-6 and Table 2-7.

For each of the conditions in Table 2-6, four cubes were sealed on five faces to allow uniaxial drying and four more were unsealed to allow triaxial drying. Weight changes were determined 4 and 18 days after the start of drying and monitored for at least 2 years. The depth of carbonation of the cubes was measured after 0,5 and 1,5 years. The water absorption of the unsealed cubes was determined after 1,5 years. A final cube was cast with 7 mm cavities for relative humidity measurements [Parrott, 1991], sealed on five of the six faces and left to dry in the same orientation as the other sealed cubes. The results of the relative humidity measurements are given in section 2.3.2.2.

Table 2-6: Scope of tests performed by Parrott [1991]

Free w:c ratio *	Cement	Period of wet curing (days)	Exposure **
0,83	OPC, OPC/PFA, OPC/GGBS	3	Lab
0,71	OPC, OPC/PFA, OPC/GGBS	3	Lab
0,59	OPC, OPC/PFA, OPC/GGBS	3	Lab, OS
0,59	OPC	3	OV, OH, Lab
0,59	OPC/PFA, OPC/GGBS	1	Lab
0,59	OPC, OPC/PFA, OPC/GGBS	28	Lab
0,59	5% filler	3	Lab, OS
0,47	OPC, OPC/PFA, OPC/GGBS	3	Lab
0,35	OPC, OPC/PFA, OPC/GGBS	3	Lab

* Free water content = 188 kg/m^3

** Lab - 60% RH, 20°C

OS - Outside, concrete exposed face sheltered

OV - Outside, concrete exposed face vertical

OH - outside, concrete exposed face horizontal

Table 2-7: Cement types used by Parrott [1991]

Cement name	Components by weight percentage	ENV 197 Cement Type	Class
OPC	100% P	CEI	42.5R
OPC/PFA	70% P + 30% A	CEIV	32.5R
OPC/GGBS	50% P + 50% S	CEIII	42.5
5% filler	95% P + 5% F	CEI	42.5R

2.3.2.1.1. Initial weight losses and diffusion in covercrete

The unsealed cubes dried significantly faster than the sealed cubes and were close to moisture equilibrium after 100 days of drying*. The sealed cubes were still drying at significant rates after 800 days. In order to compare the depths of drying of both the sealed and unsealed cubes, Parrott [1991] normalised the data by regarding the drying process as the penetration of a sharp drying front. The method he used to do this was not specified. He found that the drying depths of the sealed and unsealed cubes (after 4 days of drying) were similar.

More importantly, he established a relationship between 4 and 18 day weight losses, regardless of the surface area exposed:

$$W_{18} = 1{,}5(W_4)^{0{,}83} \qquad (2\text{-}18)$$

where W_{18} and W_4 are the weight losses after 18 and 4 days respectively (in grams of moisture)

2.3.2.1.2. Effect of w:c ratio and period of wet curing

The moisture losses increased as the w:c ratio increased, while the initial period of wet curing had an influence on weight losses at all drying ages. Initial weight losses reduced markedly as the period of wet curing was increased. This effect was most profound for OPC concretes, and when wet curing was varied between 1 and 3 days.

* The initial period of wet curing is excluded from these drying periods.

2.3.2.1.3. Initial weight loss rate and concrete properties

The sealed cubes were subjected to a water sorptivity test of 4 hours duration after 1,5 years of drying. The results, in kg/m^2, were plotted against the percentage weight loss in the first 4 days of drying and are shown in Figure 2-8. The absorption rate generally increased with initial weight loss rate, although a clear relationship is not evident for water absorption below 1,5 kg/m^2. Some of the scatter was a result of fluctuations in climatic conditions, as well as non-representative weight losses measured due to samples exposed to rain. A similar relationship was found when water absorption of the unsealed cubes was plotted against initial moisture losses.

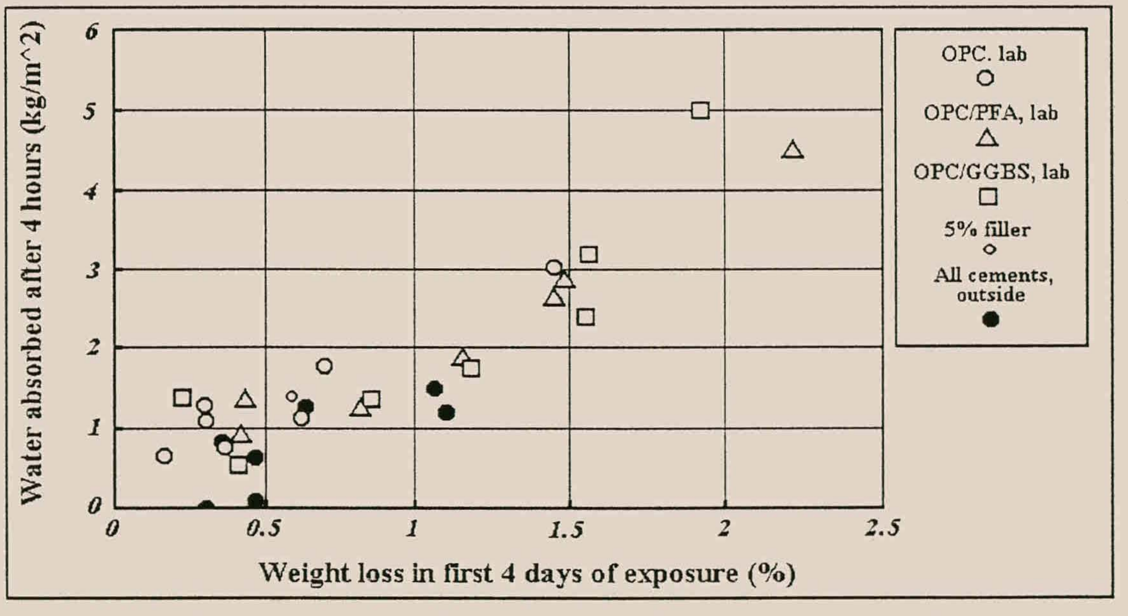


Figure 2-8: Water absorption after 1,5 years of drying versus weight loss after 4 days of drying for sealed cubes drying uniaxially [Parrott, 1991]

Air permeability was measured by pressurising a cavity in the unsealed cubes. The effective permeability was calculated from the rate at which the air permeates through the concrete to the exposed surface. In Figure 2-9 the results obtained after 80 days of laboratory exposure is plotted against moisture losses measured after 10 days of exposure (commencing at the end of the curing period). Curing periods ranged between 1 day and 1 year and cement types included OPC and binary blends containing up to 30% PFA, 50% GGBS or 5% limestone filler. It can be seen that the logarithmic value of air permeation is almost linearly related to initial moisture losses.

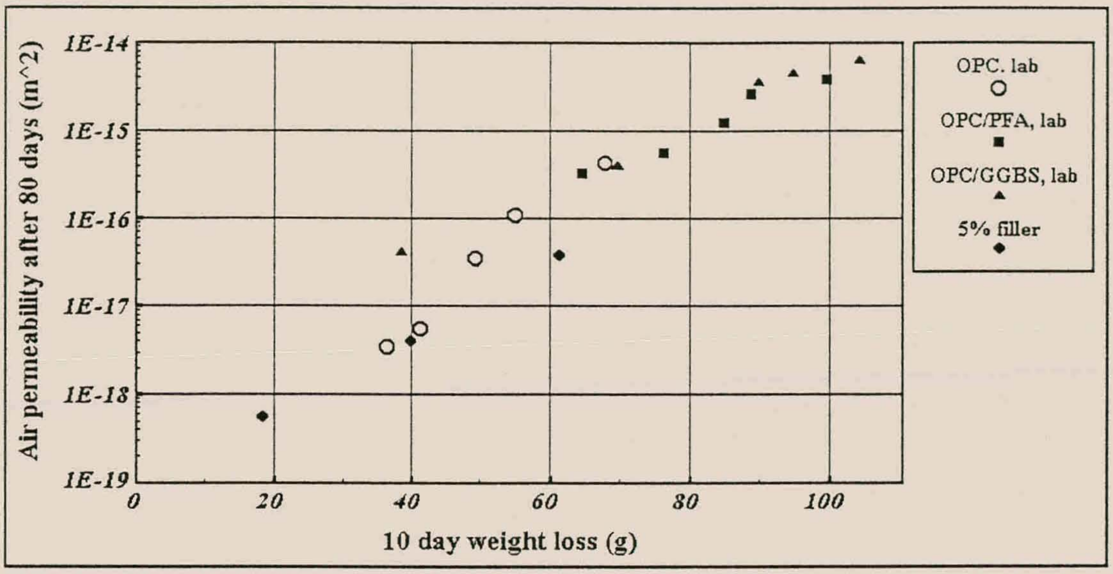


Figure 2-9: Effective air permeability of covercrete measured on cubes which were triaxially exposed for 80 days in laboratory conditions, versus weight loss measured after 10 days of drying [Parrott, 1991]

2.3.2.2. Pore relative humidities

The overall weight changes discussed in the previous paragraphs can be used when relating the average moisture condition to certain properties, but give no indication of spatial variations of moisture. During the same investigation [Parrott, 1988] pore relative humidities of the sealed cubes were measured at depths of 7,5, 11,5, 15,5, 23,5, 33,5, 53,5 and 93,5 mm. Additionally, water saturated cement paste prisms (4,4 x 4,4 x 18 mm) of the same w:c ratio were stored at these depths and weight losses were measured.

In Figure 2-10 reductions in PRH at different depths from the exposed surface are illustrated. These cubes were cured for one day and exposed to drying conditions of 20°C and 60% RH. OPC was used and the w:c ratio used was 0,59. It can be seen that after 180 days of drying, internal relative humidities were still dropping, even at a depth of 7,5 mm.

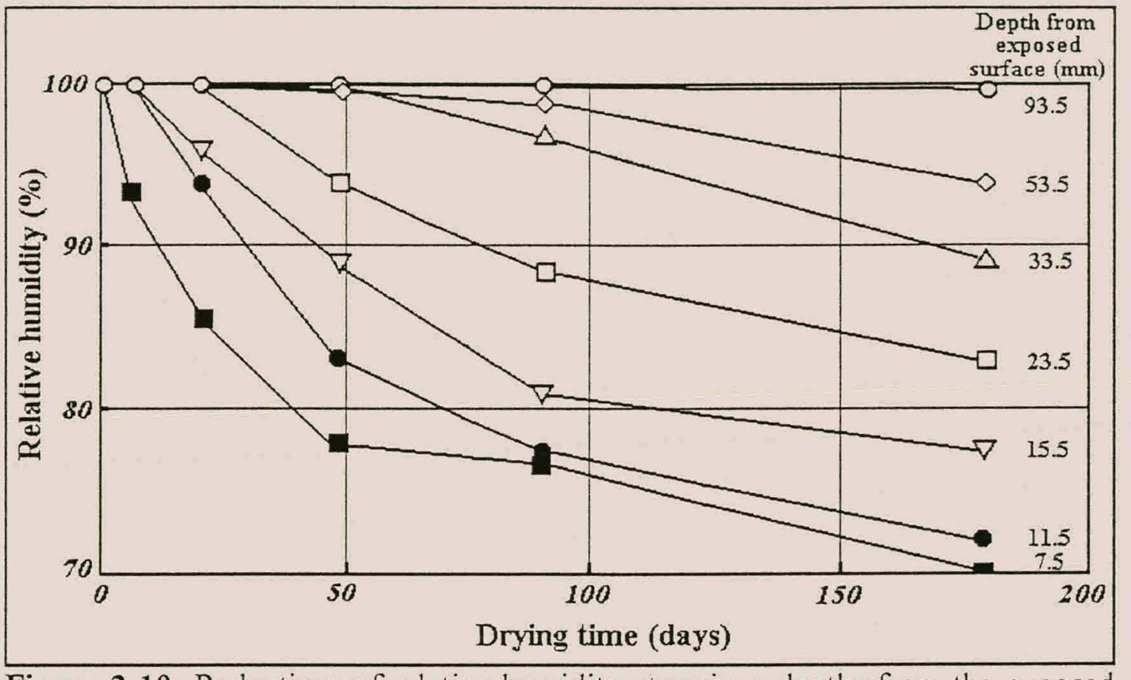


Figure 2-10: Reductions of relative humidity at various depths from the exposed surface [Parrott, 1988]

The periods (in days) taken for the internal RH to drop to 95% and 90% PRH are shown in Table 2-8. This implies that sufficient moisture for continued hydration is available at different depths for different periods of time.

Table 2-8: Time (days) for relative humidity to drop to 90% and 95% at different depths from the drying surface [Parrott, 1988]

Relative Humidity	Depth (mm)				
	7,5	11,5	15,5	23,5	33,5
90%	12	28	45	81	172
95%	4	18	24	43	111

2.3.2.2.1. Results from other investigations

Results of a similar study by Abrams and Orals [1965], measuring pore relative humidities of slabs (900 x 900 x 150 mm), cured initially in a fog room for 7 days, are summarised in Table 2-9. In this case drying times necessary to reach pre-selected relative humidities at mid-depth are presented.

Table 2-9: Effect of environmental humidity on natural drying time [Abrams and Orals, 1965]

Ambient relative humidity (%)	**Drying time to reach relative humidity at mid-thickness of 150 mm slabs (days)**		
	90% PRH	**75% PRH**	**50% PRH**
10	18	81	615
35	30	111	840
50	36	240	-
75	36	-	-

During the same investigation, slabs of 150 mm thickness were left to dry to 90% PRH at mid-depth, at ambient relative humidities of 35% and 75%. It was found that the relative humidity in the slabs decreased rapidly from a depth of 19 mm to the exposed surface, especially in the case of 35% ambient RH. The relative humidity was relatively uniform at depths 19-75 mm, and at a value above 80%. These results suggest that the OPC concrete was effectively self-curing for depths greater than 20 mm.

This was confirmed by Carrier and Cady [1970]. They conducted tests which indicated that for moderately severe field exposures (details were not specified), hydration had not ceased at a 25 mm depth after 28 days of drying.

They also demonstrated that uncured specimens dry out very quickly, as shown in Figure 2-11. It was shown that concrete at a depth of 6 mm remains above 80% for only 1 day. For 7 days of drying the 80% boundary was reached at a depth of 19 mm, and for 28 days at a depth of 50 mm.

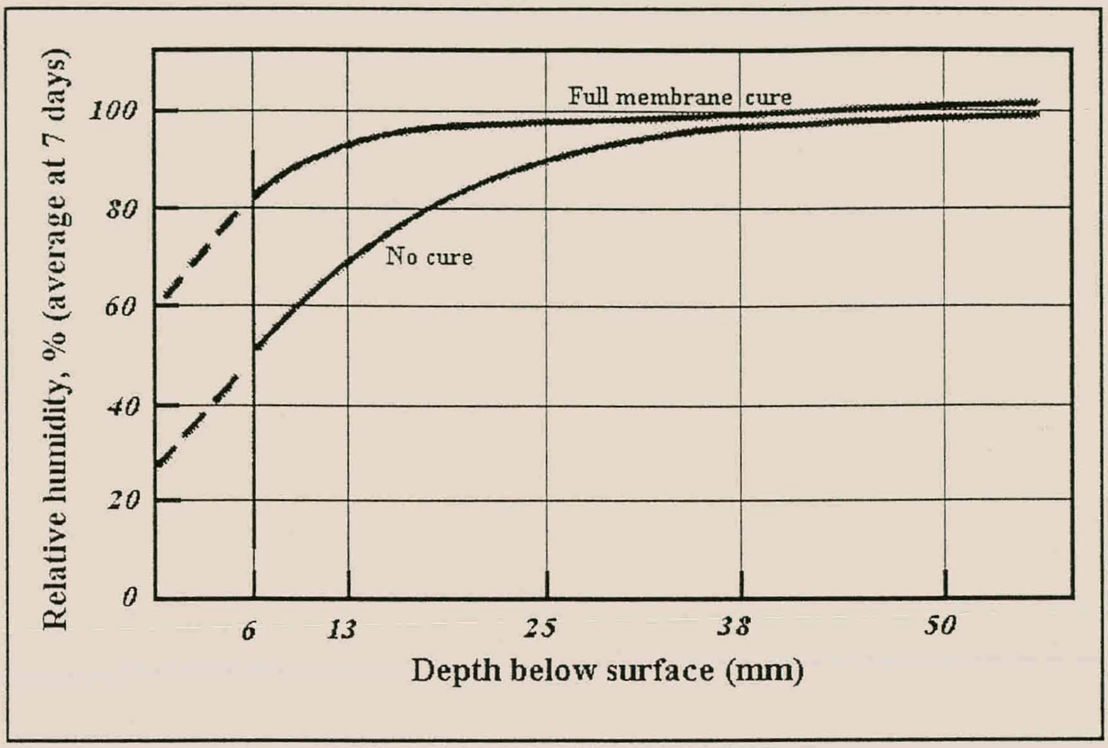


Figure 2-11: Moisture distribution after 7 days of drying [Carrier and Cady, 1970]

The first 6 mm into the concrete showed very low strength and low resistance against abrasion. Fracture was more prevalent around the aggregates rather than through them (break-out of aggregates during slicing) and microscopic examination revealed that this layer was chalky, or unhydrated.

This means that a very thin layer of the outer surface of concrete is very sensitive to wet curing. From the standpoint of wear resistance, weather resistance and appearance, this thin layer should be wet cured for as long as possible.

2.3.2.3. Moisture losses of cement paste prisms

The moisture losses of the cement paste prisms during Parrott's investigation were consistent with the foregoing results, i.e. water was lost more rapidly from prisms closer to the exposed surface, as shown in Figure 2-12. These prisms were taken from the same cubes of Figure 2-10 (drying at 20°C and 60% RH, w:c ratio 0,59, 1 day of wet curing). The prisms nearest to the surface approached weight equilibrium after 6 months of drying, while drying was much slower at depths deeper than 50 mm.

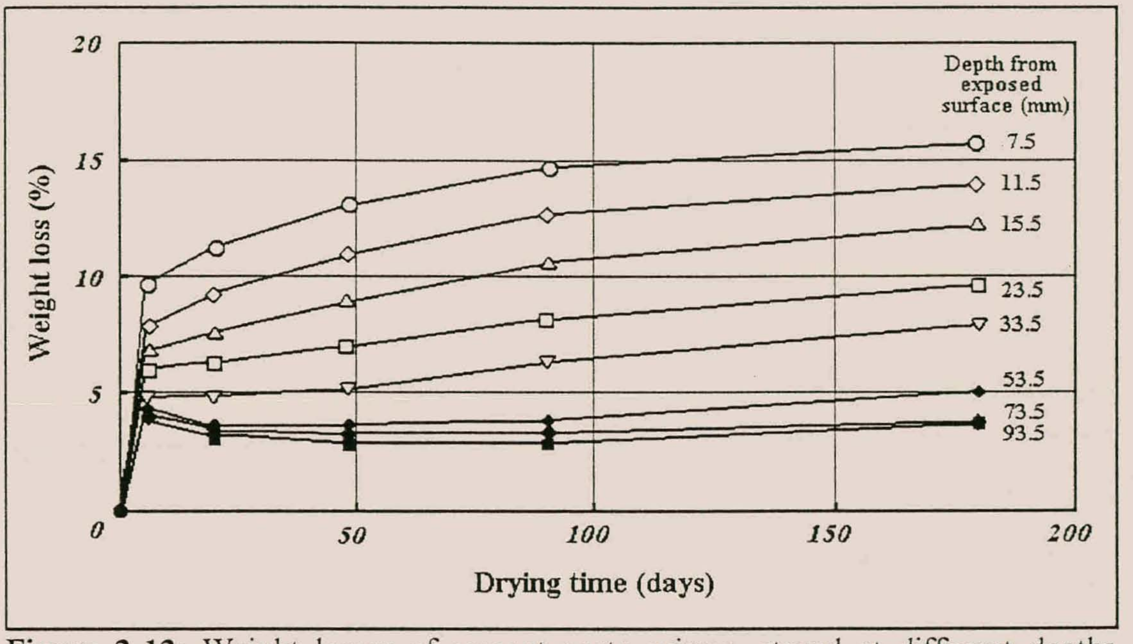


Figure 2-12: Weight losses of cement paste prisms, stored at different depths from the exposed surface [Parrott, 1988]

Another observation that was made is illustrated in Figure 2-13, where the weight losses of the prisms are plotted against relative humidity. It can be seen that prisms closest to the surface showed greater weight losses at specified relative humidities, indicating a greater volume of coarse pores in these prisms. Thus combining the methods of measuring internal relative humidities and corresponding weight losses of cement paste prisms provides a measure of porosity gradients and a means of assessing cover quality.

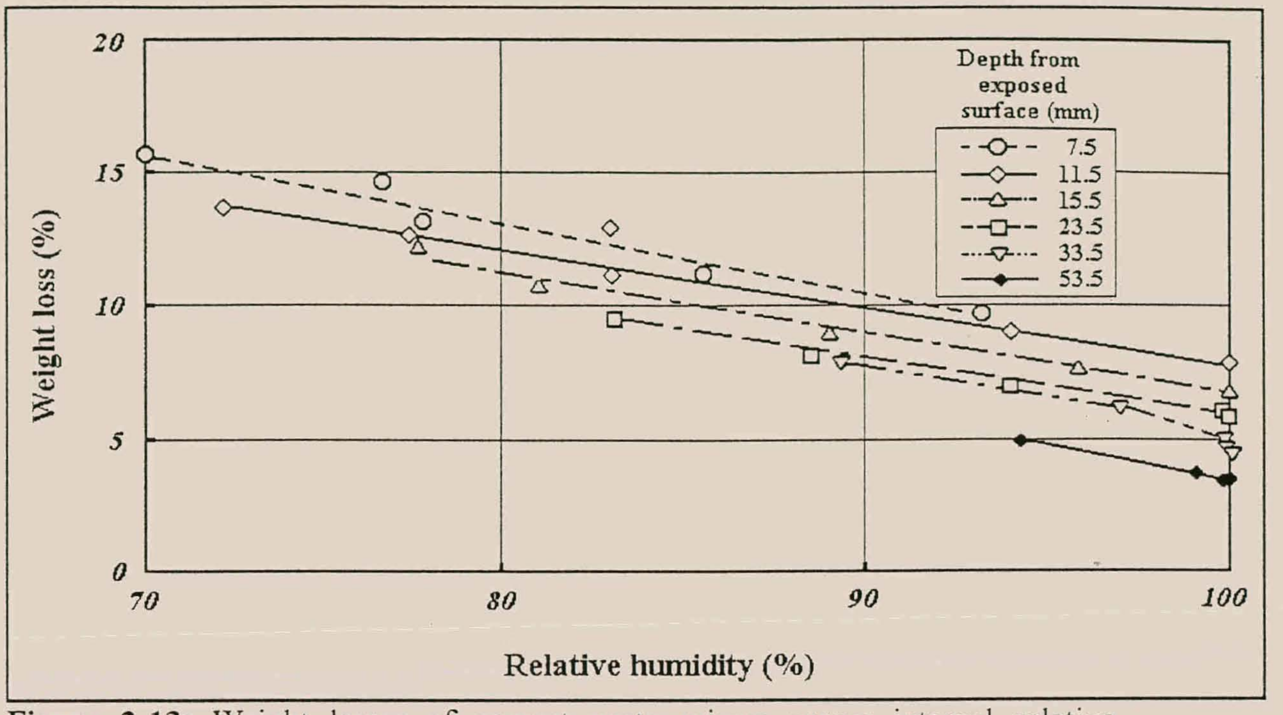


Figure 2-13: Weight losses of cement paste prisms versus internal relative humidity at different depths from the exposed surface [Parrott, 1988]

2.3.2.4. Estimation of pore relative humidities

The pore relative humidity was estimated by Parrott [1988] with the following equation,

$$PRH = RH + (100 - RH)\,f(t) \qquad (2\text{-}19)$$

where PRH = pore relative humidity

RH = ambient relative humidity

$f(t)$ = $1 / (1 + t/b)$

t = drying time (days)

b = $[d_{ex}^{1,35}(70 - e_f)(w - 0,19)] / 8$

d_{ex} = depth (mm) from the exposed surface

e_f = OPC replaced with pfa or ggbfs (%)

w = water/binder ratio

Binders :	OPC, OPC + 30% PFA, OPC + 50% GGBS
Curing times :	1, 3, 28 days
Water/binder ratios :	0,35, 0,47, 0,59, 0,71, 0,83
Drying times (excluding initial curing period):	7, 21, 49, 91, 180 days
Temperature:	20°C

This equation is only applicable under the above-mentioned conditions and predicted values of pore relative humidities were generally within 4% of the measured values. In Figure 2-14 equation 2-19 is plotted for w:c ratios of 0,84, 0,56 and 0,40* to illustrate the effect of w:c ratio on the pore relative humidities of concrete at different depths. The ambient relative humidity is 60%, no extenders were used (e=0) and the drying time is 7 days.

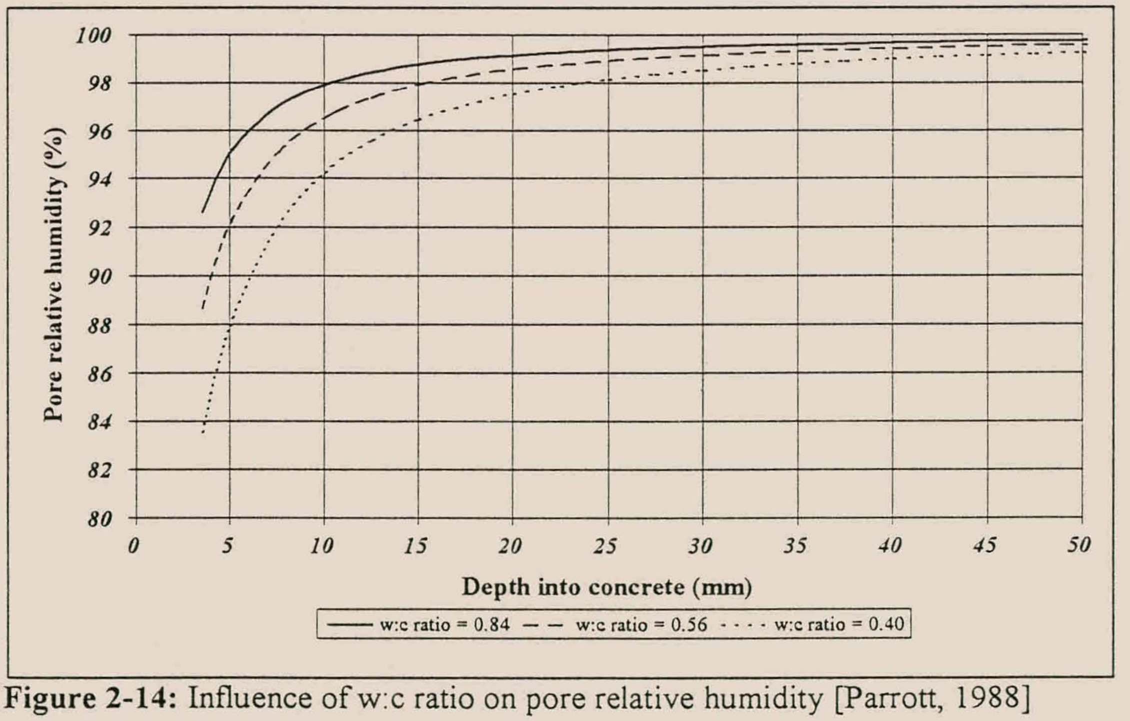


Figure 2-14: Influence of w:c ratio on pore relative humidity [Parrott, 1988]

* These were the w:c ratios used during the current project.

Two noteworthy comments on this graph and equation are:

1. The lower the w:c ratio, the lower the pore relative humidity for a given time, ambient relative humidity and depth from exposed surface.
2. The period of wet curing has no effect on the pore relative humidity [Parrott, 1988]. This seems to be a contradiction of Figure 2-11, where full membrane curing made a significant difference in pore relative humidities, after 7 days of drying. It is also a contradiction of the fact that shorter curing periods lead to greater moisture losses.

The first point can be explained by the rate at which water is taken up by the hydration process. The more cement available for hydration, the more is the water chemically bound in hydration products. At very low w:c ratios, self-desiccation takes place. This means that the lower pore relative humidities of concretes with low w:c ratios, are caused by increased rates at which water is consumed by the hydration process. Thus this moisture is not lost through evaporation and is therefore not really a component of the type of drying that this investigation is concerned with.

The second point is more difficult to explain. Parrott's [1988] opinion is that high permeability is accompanied by increased amounts of pore water to be evaporated, whereas lower permeability results in more effective retention of pore water. This can be visualised by assuming the total porosities (capillary + gel porosity) of well - and poorly cured concretes (of the same w:c ratio) to be similar, thus implying similar amounts of pore water. In the case of poorly cured concretes, a larger volume fraction of the total porosity would consist of capillaries than in the case of well-cured concretes. In other words, these effects are counter-balancing as far as internal relative humidity of concrete is concerned.

Although this seems to be a reasonable explanation, the contradictions mentioned in 2. (above) indicate that the calculation of pore relative humidities with equation 2-19 is only a rough estimation of the true moisture distribution in the covercrete.

2.3.3. The influence of environmental conditions on drying processes in concrete and HCP

The evaporation of pore water from concrete is governed by temperature, relative humidity and possibly wind speed, as well as the pore size distribution of the cement paste. The mechanism of evaporation from capillary pores is discussed first, followed by the influence of environmental conditions on the rate of evaporation.

2.3.3.1. Evaporation from capillary pores

The relationship between temperature, relative humidity and the radius of menisci formed in capillaries is given by Kelvin's equation [Soroka, 1979]:

$$\ln\left(\frac{P}{P_0}\right) = \frac{2\tau M}{RT\rho r} \tag{2-20}$$

where P_0 = saturation vapour pressure
P = vapour pressure
τ = surface tension of the liquid (0,072 newton/m for water)
M = molecular mass of the liquid (0,018 kg/mole for water)
R = universal gas constant (8,3143 joule/mole.Kelvin)
T = temperature (Kelvin)
ρ = density of the liquid (1000 kg/m^3 for water)
r = radius of meniscus formed in the capillary (m)

The implication of this equation is that at 100% RH, the surface of the water in the capillary is plane ($r = \infty$) and no evaporation takes place. As the vapour pressure drops below 100%, the water in the capillary evaporates until equilibrium is reached, in other words until the radius of the meniscus corresponds to the relative humidity. However, r cannot be smaller than the radius of the pore. Hence, if the vapour pressure drops below that corresponding to the radius of the pore, evaporation takes place until the capillary is dry. Since the smallest possible radii form in the smallest pores, water is first lost from the bigger pores and only later from the smaller pores. Additionally, menisci cannot exist at relative humidities lower than 45% [Powers, 1960], due to the small size of capillaries still containing moisture at these relative humidities (diameters of approximately 2,5 nm).

In Figure 2-15 temperature and relative humidity (P/P_0) are plotted against the corresponding values of r of the Kelvin equation. Note that the values for r in this figure are > 0, when they are actually negative when calculated from equation 2-20.

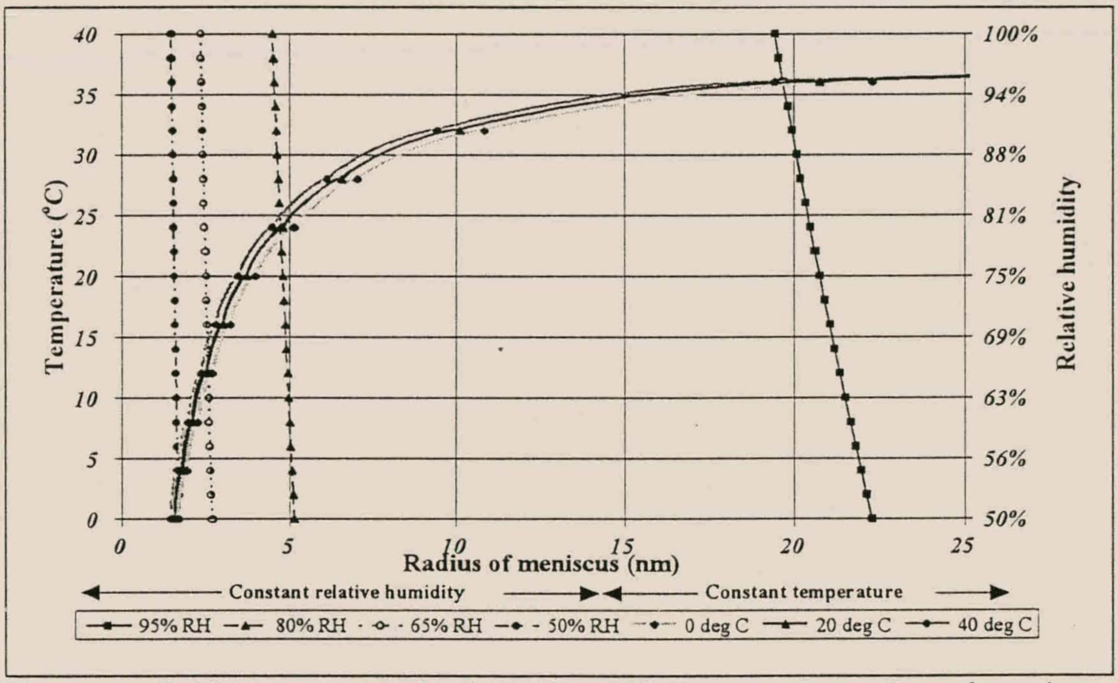


Figure 2-15: Temperature and relative humidity versus the radius of meniscus formed in capillaries (Kelvin equation)

Figure 2-15 indicates the evaporation from capillaries to be a process largely controlled by relative humidity, while temperature plays only a minor role. However, equation 2-20 gives no indication of the *rate* of evaporation. In other words, this equation can be used to describe the drying of hardened concrete, but not to indicate the rate at which the process occurs. In order to understand the significance of temperature and relative humidity on concrete drying, their effects on both capillary size and rate of evaporation have to be taken into consideration.

2.3.3.1.1. The influence of relative humidity

In capillary pores, the vapour pressure over the meniscus differs from that over a plane surface. Greater forces and consequently lower vapour pressures are necessary to cause evaporation, in the case where a meniscus is formed.

The influence of pore relative humidity on the porosity of HCP

Referring back to Table 2-2, the bulk of capillary sizes in HCP vary in size from 10 nm to 1 mm (in diameter). A pore relative humidity of 80% corresponds to a pore diameter of approximately 10 nm (or a radius of 5 nm), at 20°C. Thus, as the pore relative humidity in concrete drops from 100% to 80%, theoretically almost the entire capillary porosity is emptied by evaporation.

Additionally, the rate of cement hydration decreases markedly with small reductions in internal relative humidity [Parrott, 1988]. Parrott found that at 90% PRH the hydration rate is approximately half of the rate in a saturated state. On the other hand, it was observed that no reduction in porosity took place below 95% PRH. This statement seems odd when one considers the fact that a significant amount of hydration is still taking place at such high relative humidities.

Work done by Patel et al [1988] provided experimental data to confirm Parrott's observations. Slices of HCP (w:c ratio of 0,59) of 3 mm thickness were conditioned at relative humidities ranging from 33% to 100%. The porosities of these slices were determined 14 and 90 days after casting. Distinctions were made between gel porosity (diameter < 4 nm), small porosity (pore diameter < 37 nm) and large porosity (pore diameter > 37 nm). The conditioning temperature was 20°C.

Gel and small porosities increased with increasing relative humidities, while the large porosity decreased. Thus continued hydration leads to the formation of a larger volume of cement gel (larger gel porosity), filling capillaries and increasing the volume of pores smaller than 37 nm (larger small porosity), while the volume of larger capillaries (and thus the large porosity) reduces. In the cases of gel and large porosity, significant changes took place only at 95% RH and above. Small porosity started increasing significantly above 91% RH.

The above information provides a means for calculating effective curing periods at different depths into the concrete. Additional time (in days) to reduce to 95% PRH, at any depth, can be calculated with the aid of equation 2-19 and added to the initial wet curing period. Unfortunately, this equation is only valid at 20°C and not dependent on wet curing, thus the influences of temperature and wet curing will have to be assessed if a more exact answer is required. Additionally, other voids (bleeding channels, honeycombing and pockets and cavities under aggregates and reinforcing bars), occur to a greater or lesser extent and will also influence moisture profiles in hardened concrete.

2.3.3.1.2. The influence of temperature

Temperature influences the evaporation process by supplying water molecules with energy to evaporate. The higher the temperature, the smaller the diameter of a pore that can be emptied by evaporation. This is more significant at higher relative humidities (Figure 2-15).

At 95% PRH and 0°C, capillaries with radii of approximately 22-23 nm can be emptied. At 40°C the radius decreases to approximately 19-20 nm. At 50% PRH there is virtually no difference in the corresponding values for the radius of the meniscus at 0 and 40°C. Thus it seems as if temperature has little effect on the radius of pores that will empty, i.e. virtually irrespective of temperature, all pores of a given size (and above) will be emptied by evaporation.

2.3.3.2. The rate of evaporation

While the pore relative humidity and temperature determine the *pore sizes* from which evaporation occurs, these effects also influence the *rate of evaporation* of the pore water. In other words, capillaries will also empty at faster or slower rates, depending on the severity of their neighbouring environment.

2.3.3.2.1. The influence of temperature and relative humidity on the rate of evaporation

In the *ACI Manual of Concrete Practice* [ACI 305R-96], a nomograph is given to estimate the rate of evaporation of *free* water* from fresh concrete surfaces, for the purpose of predicting plastic shrinkage cracking (Figure 2-16). In hardened concrete, these evaporation rates are only applicable at the start of exposure, when the surface pores are still saturated. As soon as the pore relative humidities reduce to less than 100%, menisci are formed and larger forces are required for evaporation, i.e. the rate of evaporation decreases. The influence of wind speed is more significant for fresh concrete than for hardened concrete, and is discussed in section 2.3.3.2.3.

* Free surface water is not confined in pores, and no meniscus is formed.

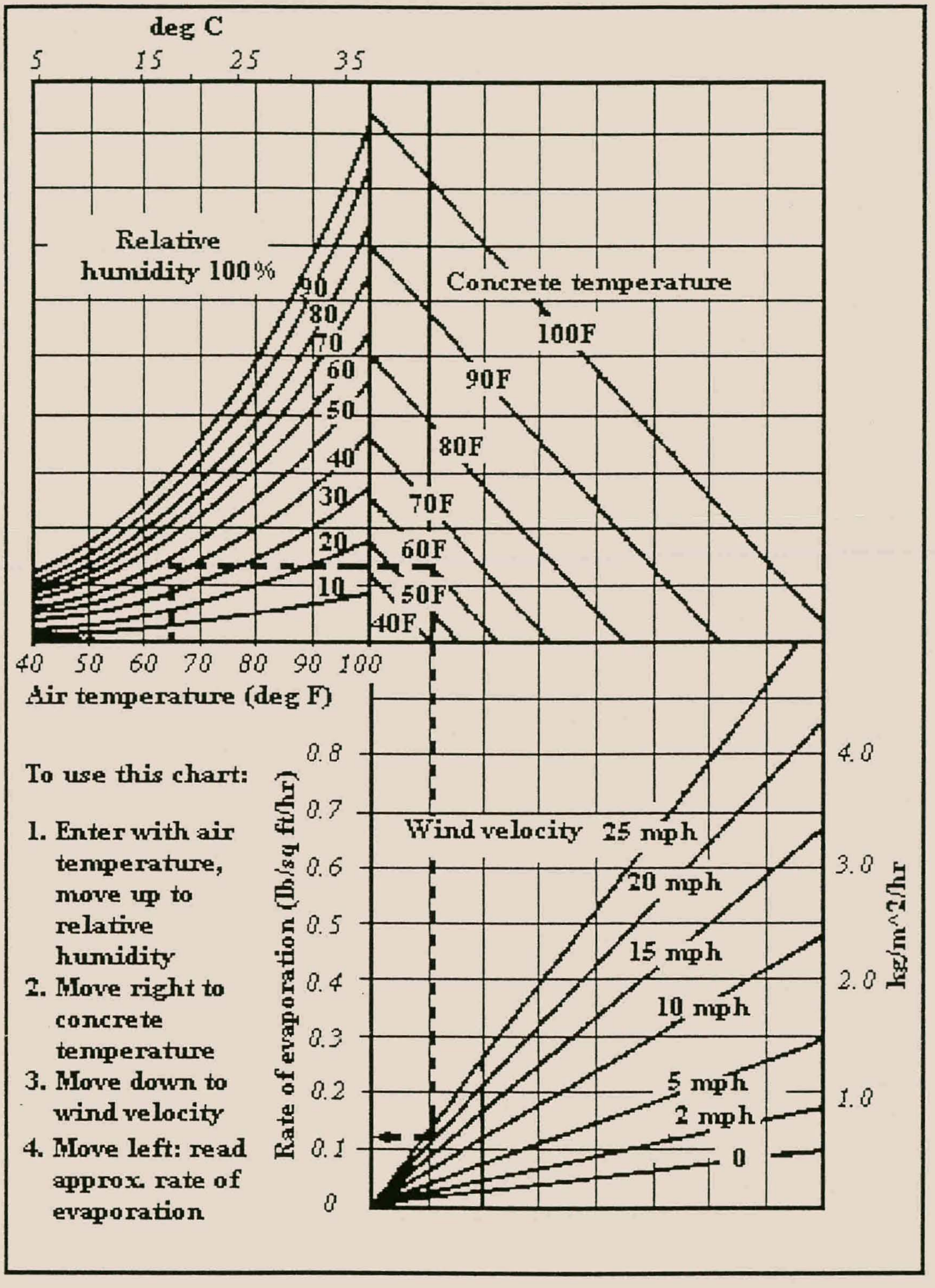


Figure 2-16: ACI nomograph for estimating rate of evaporation of surface moisture from concrete [ACI 305R-96]

Figure 2-16 provides a helpful means for assessing the importance of temperature and relative humidity on the severity of different drying conditions. This can be done by using the original equations of Figure 2-16, given by Uno [1998]:

$$P_0 = 0.61e^{\frac{17,3T}{237,3+T}} \tag{2-21}$$

where P_0 = saturation vapour pressure (kPa)

T = temperature (°C)

and

$$E = 0,313(P_{0so} - RH \cdot P_{0sa})(0,253 + 0,06v) \tag{2-22}$$

where E = rate of evaporation (kg/m^2/hr)

P_{0so} = vapour pressure at concrete surface (kPa) from equation 2-21

P_{0sa} = vapour pressure of air (kPa) from equation 2-21

RH = (relative humidity, %) / 100

v = wind velocity (kph)

When the drying of hardened concrete is considered, the air and concrete temperatures can be taken as the same value, thus $P_{0so} = P_{0sa}$. If wind speed is left out of the above equations ($v = 0$), equations 2-21 and 2-22 can be combined to yield:

$$E = 7,919 \cdot 10^{-2}\left[0,61e^{\frac{17,3T}{237,3+T}} - RH\left(0.61e^{\frac{17,3T}{237,3+T}}\right)\right] \tag{2-23}$$

This equation can be rearranged to yield an expression for relative humidity in terms of the rate of evaporation and temperature, i.e.:

$$RH = -20{,}702\left[\frac{E - 4{,}831\cdot 10^{-2}\, e^{\frac{17{,}3T}{237{,}3+T}}}{e^{\frac{17{,}3T}{237{,}3+T}}}\right] \tag{2-24}$$

Equation 2-24 can be used to illustrate the significance of temperature and relative humidity on the rate of evaporation of free surface water. By substituting different values for the rate of evaporation, various functions of *RH = f(T)* can be obtained, and is done in Figure 2-17.

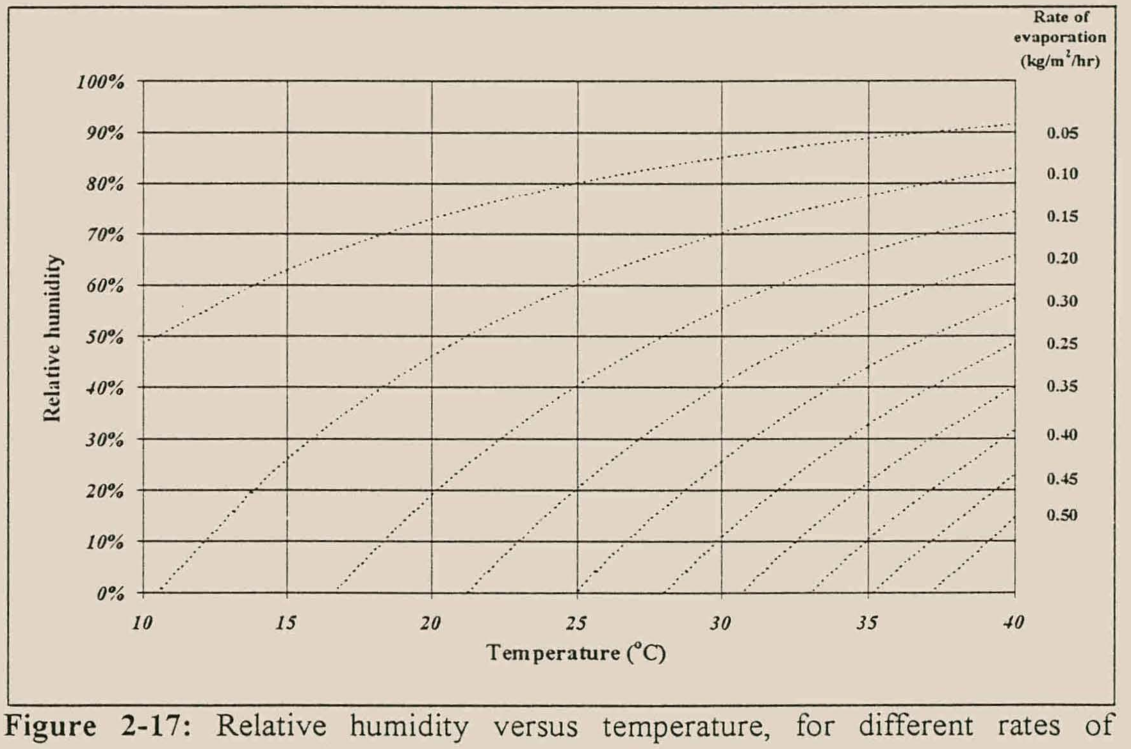


Figure 2-17: Relative humidity versus temperature, for different rates of evaporation [Uno, 1998]

The data in Figure 2-17 demonstrates the interaction between temperature and relative humidity on the rate of the evaporation process. The influence of relative humidity increases with increasing temperature, and the influence of temperature increases with decreasing relative humidity. For example, at 20°C the difference in rate of evaporation between 50% and 80% is approximately 0,05 kg/m^2/hr, with a difference of 0,25 kg/m^2/hr at 40°C. Similarly, the rate of evaporation between 20 and 40°C differs with approximately 0,08 kg/m^2/hr at 80% RH, with a difference of approximately 0,15 kg/m^2/hr at 50% RH.

2.3.3.2.2. The rate of evaporation from hardened concrete

The information given by equations 2-21 to 2-24 and Figure 2-17 is applicable for the rate of evaporation of free surface water, where no meniscus is formed. As already mentioned, the rate of evaporation will decrease as soon as the pore relative humidity drops below 100%, as determined by the pore structure of the concrete. The smaller the pores, the larger the surface tension forces generated and the slower the rate of evaporation. In other words, the rate of evaporation is influenced firstly by the severity of the surrounding environment, and secondly on the properties of the concrete.

The rate of moisture loss is therefore dependent on:

- The pore sizes.
- The severity of the surrounding environment.
- The internal humidity gradient that causes hydraulic tension forces. The magnitude of these forces and the pore size distribution of the concrete determine the rate of diffusion of moisture from deeper regions in the concrete to exposed surfaces. As the internal relative humidity reduces, the transport mechanism changes from capillary action to vapour diffusion, surface diffusion and finally molecular migration. Thus the forces required to transport molecules to the surface increase and rate of moisture loss decreases with time.

The rate of hydration is also a function of temperature, and increases with increasing temperature [Soroka, 1979]. Thus covercrete properties develop at faster rates at elevated temperatures, but pore water is also lost more rapidly to evaporation. These two effects are in competition, and concrete can either benefit or develop poor durability properties at elevated temperatures, depending on the severity of the environment and the ability of the concrete to retain its moisture. The latter depends on the inherent microstructure of the cement paste and improves with lower w:c ratios and longer periods of wet curing. The interaction between the concrete and the environment is schematically illustrated in Figure 2-18.

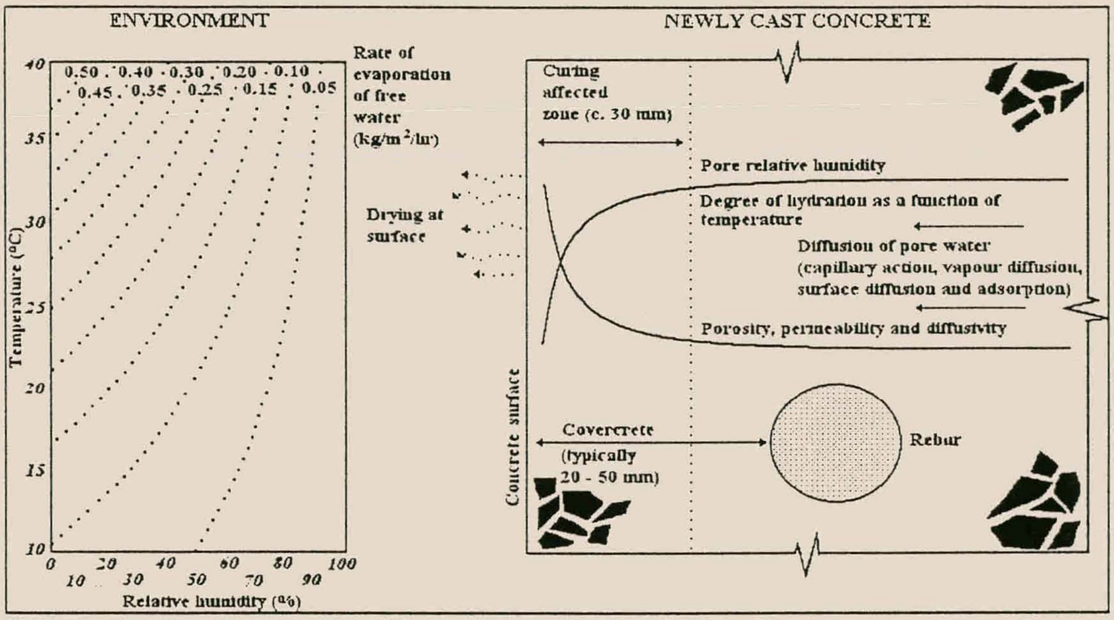


Figure 2-18: Schematic illustration of the interaction between newly-cast concrete and the environment

2.3.3.2.3. The influence of wind speed

As seen in Figure 2-16, the rate of evaporation from a free water surface is dependent on wind speed. No literature could be found which discusses its influence on drying processes in hardened concrete. The author is of the opinion that wind only affects the rate of evaporation from the surface of the hardened concrete. Thus wind should only have an effect on moisture loss for as long as pore water is located in capillaries open to the surrounding environment. This would be the case in concretes with w:c ratios higher than 0,70 and/or poorly cured concretes, with large degrees of interconnection of capillaries [Verbeck, 1978].

2.4. The influence of environmental conditions on the potential durability of concrete

This investigation is concerned with the determination of the influence of environmental conditions on the potential concrete durability. In particular, the influence of relative humidity, temperature and wind speed, are considered. In a study conducted by Ho et al [1989], the influence of relative humidity on covercrete performance was investigated. No literature could be found on the influences of temperature and wind speed on covercrete performance.

In Ho's study, concrete samples of 32 MPa compressive strength (cylinders of dimensions 400 x 170 x 60 mm) were wet cured* for 1 day and then exposed to relative humidities of 50, 65, 75, 84 and 94%. Temperatures were maintained at 23°C, and water sorptivity tests were conducted after 91 and 365 days of drying. The water absorption test involved subjecting one face of the specimen to continuous water spray at an air pressure of 0,5 kPa. The depths of water penetration were noted visually by splitting specimens at periods of 0,5, 2, 4, 8, 16 and 24 hours. Typical results for this investigation are shown in Figure 2-19.

* During this study, concrete samples were enclosed in a plastic envelope for 24 hours after casting, and thereafter curing was continued in a fog room.

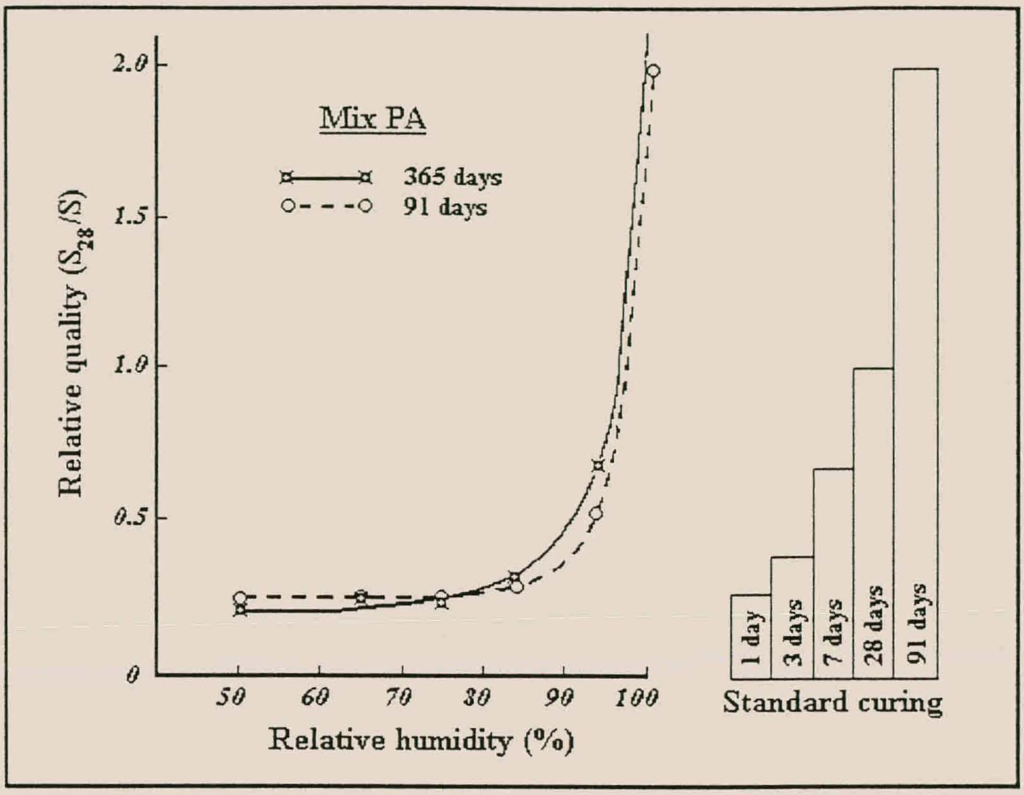


Figure 2-19: Quality achieved by concrete exposed to different relative humidities [Ho et al, 1989]

Sorptivity results for standard curing regimes of 1 day, 3 days etc. are also given in Figure 2-19. The results show that below a relative humidity of 75% there was no improvement in the sorptivity results, compared to 1 day of a standard curing regime. This suggests that negligible cement hydration has taken place. At 84% RH there was a marginal increase in concrete quality*. However, hydration is still very slow at this level. Even after 1 year of drying at 84% RH, the results achieved were still below that obtained with three days of wet curing. When samples were exposed to 94% RH for 1 year, results were equivalent to those obtained for 7 days of wet curing. In practical terms this means that concrete samples have to be exposed to near saturated conditions (94% RH) for a year, in order to obtain results similar to samples which were initially wet cured for 7 days.

* In this context, concrete quality is defined as the resistance of the concrete to water penetration.

2.5. Assessing the influence of environmental conditions on the potential durability of concrete

The previous sections examined the information available on the hydration process and the development of the hardened concrete properties. It has been shown that the drying process and the factors which influence this, have a direct effect on the potential durability.

The development of the durability index tests of Alexander et al [Bouwer, 1998] provides a powerful new experimental procedure to assess potential durability. However, these tests have not yet been calibrated in respect of environmental conditions. The purpose of this project is to implement the first stages in this calibration.

2.5.1. Measuring concrete durability

The primary objective of this investigation was to determine the influence of environmental conditions on the potential durability of concrete. Denser pore structures will lead to lower water absorption rates, lower permeability to oxygen and carbon dioxide, as well as lower penetrability to aggressive agents such as chlorides. Measuring of the covercrete's performance with respect to these processes can therefore be used to assess the influence of temperature, relative humidity and wind speed on the potential durability of hardened concrete.

2.5.2. Experimental approach

In the past material durability studies were based on long-term laboratory and degradation case studies, comparing behaviour under both similar and different conditions. However, during the past three decades, the aim has moved towards research on material properties and the prediction of service life through mathematical modelling [Oberholster, 1986].

Such mathematical models are calibrated by systematic scientific research, based on carefully designed experiments. In this respect it is important to define the material in terms of composition and manufacturing process. The number and significance of degradation factors must be established and consequences of each mechanism characterised. It is further necessary to establish a quantitative indicator of degradation, establish how it can be measured and devise an accelerated test to simulate the appropriate mechanism and [Oberholster, 1986].

The properties of reinforced concrete are determined by the nature of its components, which are cement, water, coarse aggregate, sand, chemical and mineral admixtures and additives and steel reinforcement, as well as by mixing, placement, compaction and curing. Any measured property relates to a specific concrete, and is therefore a function of all the above. The determination of the influence of any one variable requires that all others be kept constant.

This is the approach to be used in this project. Three concrete properties will be investigated, which are:

- Porosity.
- Diffusivity.
- Permeability.

2.5.3. Index testing of concrete for control of durability

The prediction of the long-term durability and serviceability of reinforced concrete structures has become an important issue for engineers and designers. This is a result of the relatively poor service performance of modern reinforced concrete structures [Alexander, 1997].

In the past, the use of compressive strength was used as a simple quality control test. Although this test bears little resemblance to the state of stress existing in a real structure, experience has compensated for its shortcomings [Alexander, 1997]. At present, the prediction of structural performance, in terms of strength, can be done with reasonable confidence. Therefore, the compressive strength of a concrete cube or cylinder can be classified as an 'index' test, characterising the potential of the material to resist applied stress [Alexander, 1997].

However, the compressive strength measures the overall bulk response of the material to stress [Alexander, 1997], and gives no indication of the covercrete's ability to protect the reinforcing steel. It was therefore necessary to develop a range of index tests, which characterised the covercrete's penetrability to agents inducing and aggravating steel corrosion.

Three durability index tests have been developed at the Universities of Cape Town and the Witwatersrand [Bouwer, 1998], which are the chloride conductivity test, the oxygen permeability test and the water sorptivity test. These index tests were used to evaluate the durability properties of the covercrete, and for the assessment of the influences of temperature, relative humidity and wind speed during initial drying on its potential durability.

2.5.3.1. Sample preparation for the durability index tests

The concrete samples used for these tests are cylindrical cores of 68 mm diameter and 25 mm thickness. These are oven dried at 50°C and 15% RH prior to testing, until the change in mass is less than 0.1% over a 24 hour period [Alexander and Magee, 1999].

2.5.3.2. The chloride conductivity index test

This test involves determining of the conductivity of concrete specimens, from their dimensions and electrical resistance. The samples are saturated with a 5 M NaCl solution prior to testing, by submersion under vacuum (-80 kPa) for 24 hours. The test procedure is to apply a potential of 10 V across the ends of the specimen and measuring the electrical current (DC) passing through. This is achieved using a conduction cell filled with 5 M NaCl solution.

2.5.3.3. The water sorptivity index test

Sorptivity can be defined as the rate of movement of a water-front through a porous material under capillary action [Alexander and Magee, 1999]. The water sorptivity test involves the saturation of layers of absorbent material in a plastic tray, with a distilled water / $Ca(OH)_2$ solution. The pre-conditioned concrete samples are placed onto the saturated material, and their mass gain monitored at prescribed time intervals [Bouwer, 1998]. An electronic scale, accurate to 10 milligrams, is used for this purpose. The sides of the samples are sealed prior to testing, to ensure uniaxial absorption. The water sorptivity index is calculated using the dimensions of the specimen, its porosity* and the absorption rate in grams / √time. The physical interpretation of this index is the rate of penetration of the water-front, in mm / √h.

2.5.3.4. The oxygen permeability index test

This test involves determining the rate at which oxygen permeates through a concrete sample. An initial oxygen pressure head of approximately 100 kPa is applied across the sample, using a falling head permeameter [Alexander and Magee, 1999]. The pressure decay with time is measured, and the Darcy coefficient of permeability is determined. The oxygen permeability index is the negative logarithm of the coefficient of permeability.

* The porosity is determined by vacuum saturation of the samples in distilled water / $Ca(OH)_2$ solution after testing, and is equal to (saturated mass – dry mass) / dry mass.

2.5.4. Other methods for assessment of performance and degradation of reinforced concrete structures

Other principal test methods to assess the corrosion of reinforcement, concrete quality, durability and deterioration, as well as the integrity and performance of concrete structures, are summarised in Table 2-10. However, none of these were evaluated for possible use in this investigation.

Table 2-10: Basic characteristics of principal test methods [Glanville, 1995]

Property under investigation	Test	Equipment type
Corrosion of reinforcement	Half-cell potential	Electrochemical
	Resistivity	Electrical
	Linear polarisation resistance	Electrochemical
	Cover depth to reinforcement	Electromagnetic
	Carbonation depth	Chemical and microscopic
	Chloride penetration depth	Chemical and microscopic
Concrete quality, durability and deterioration	Surface hardness	Mechanical
	Ultrasonic pulse velocity	Electromechanical
	Radiography	Radioactive
	Radiometry	Radioactive
	Permeability	Hydraulic
	Absorption	Hydraulic
	Moisture	Chemical and electronic
	Petrographic	Microscopic
	Sulphate content	Chemical
	Expansion	Mechanical
	Air content	Microscopic
	Cement type and content	Chemical and microscopic
	Abrasion resistance	Mechanical
Integrity and structural performance	Tapping	Mechanical
	Pulse-echo	Mechanical/electronic
	Dynamic response	Mechanical/electronic
	Thermography	Infra-red
	Radar	Electromagnetic
	Reinforcement location	Electromagnetic
	Strain or crack measurement	Optical/mechanical/ electrical
	Load test	Mechanical/electronic/ electrical

2.6. Summary

2.6.1. Factors influencing concrete durability

In the context of this study, the potential durability of concrete can be defined as the properties of the covercrete influencing the penetration and transportation of moisture, gases and chloride ions to the reinforcing steel, i.e. porosity, permeability and diffusivity. These properties are affected by the characteristics of the hardened cement paste, the aggregate, the paste-aggregate interface and defects caused by the manufacturing of concrete.

In this project the influence of environmental factors in the post-curing phase is investigated. The potential durability of the concrete subjected to different environmental conditions will be evaluated, using the three durability index tests previously discussed.

In the following section the various which influence the development of durable concrete in the post-curing phase, are summarised.

2.6.1.1. The properties of the cement paste

The properties of the cement paste are dependent on sufficient moisture, the w:c ratio, time and temperature. The porosity of HCP decreases with continued hydration. This leads to the pores in the fresh cement paste being filled with hydration products, reducing the pore sizes and also the degree of interconnection between pores. The decreasing porosity of the HCP reduces the rate at which aggressive agents can enter and diffuse through the material, increasing its durability properties.

2.6.1.2. The properties of hardened concrete

Hardened concrete consists of HCP, aggregates and entrapped voids. The cement gel has a porosity of 28%, while the porosity of the aggregate is typically between

1% and 5%. Therefore the pores in concrete consist of gel pores, capillary pores, entrapped pores, entrained pores and pores in the aggregate. The resulting porosity of concrete ranges between 7% and 15% for very good and average quality concretes respectively.

The porosity of aggregates is generally lower than that of the HCP, and moisture diffusion is rather a function of the properties of the cement paste / aggregate interface than the porosity of the aggregate. The inclusion of aggregates effectively increases the permeability of HCP.

Voids other than gel, capillary and aggregate pores also occur to a greater or lesser extent, depending on the quality of the mix design and manufacturing process. These are bleeding channels, pockets and cavities under aggregates and reinforcing bars, as well as honeycombing.

2.6.1.3. Moisture diffusion

The evaporable water in hardened concrete can be divided into adsorbed and interlayer water, as well as mobile (capillary condensed) water. This component of the pore water is transported through hardened concrete by means of adsorption, surface diffusion, vapour diffusion, capillary action and bulk flow (in saturated conditions).

2.6.1.4. The covercrete

The durability of reinforced concrete structures depends largely on the properties of the outer 'skin' of concrete, or covercrete (typically the outer 20 - 50 mm of the concrete). The properties of the covercrete are dependent on factors such as water:binder ratio, binder content and binder type.

2.6.2. The effect of curing on covercrete performance

In previous work [Ballim, 1993] it was found that:

- Wet curing had a significant influence on the oxygen permeability of concrete. Lack of curing could cause an increase of up to 50 times in oxygen permeability.
- The extent of moist curing had a considerable effect on water sorptivity, although not quite as much as in the case of oxygen permeability.

Other investigations [Grube and Lawrence, 1984] indicated that the oxygen permeability after 3 days of wet curing, compared to 1 day of wet curing, had decreased by 5 times (on average) and by 9 times after 28 days of wet curing.

In another study [Ho et al, 1989], water sorptivity was used to describe concrete quality, and to determine the influence of wet curing on potential concrete durability. The results of this investigation indicated that concrete quality was doubled by increasing curing from 1 to 7 days, and quadrupled by extending curing to 28 days. After 91 days of wet curing, sorptivity results indicated a concrete of quality double that achieved after 28 days of wet curing.

2.6.3. Drying processes

2.6.3.1. Overview of the drying of concrete and HCP

When newly cast concrete is first exposed to the environment, i.e. ideally at the end of the curing period, an immediate humidity gradient is established between the saturated pores of the concrete and the surrounding environment. Water starts evaporating from the surface layers, and a humidity gradient is established inside the concrete. For as long as sufficient moisture is available at deeper regions, hydration continues and the porosity of the concrete decreases.

The capillary sizes from which evaporation occurs are dependent on the temperature and relative humidity of the surrounding concrete. Larger pores are emptied first and smaller pores later. The humidity gradient in the concrete results in hydraulic tension forces and water molecules diffuse towards the exposed surface by the adsorption, surface diffusion, vapour diffusion and capillary action.

While the pore relative humidity and temperature governs the *pore sizes* from which evaporation occurs, these effects also determine the *rate of evaporation* of the pore water. In other words, capillaries larger than the size governed by these effects, also empty at faster or slower rates, depending on the severity of their neighbouring environment.

Wind speed might also have an influence on moisture loss from hardened concrete, since it affects the rate of evaporation of moisture. However, its influence would not be able to penetrate much deeper than the immediate concrete surface and it is not expected to have any significant influence.

2.6.3.2. The influence of environmental conditions on drying processes in concrete and HCP

At 100% PRH, the surface of the water in the capillary is plane and no evaporation takes place. As the vapour pressure drops below 100%, the water in the capillary evaporates until equilibrium is reached, in other words until the radius of the meniscus corresponds to the relative humidity (given by equation 2-20). When the vapour pressure drops below that corresponding to the radius of the pore, evaporation takes place until the capillary is dry. Since the smallest possible radii form in the smallest pores, water is first lost from the bigger pores and only later from the smaller pores. Additionally, menisci cannot exist at relative humidities lower than 45%, due to the small size of capillaries still containing moisture at these relative humidities (diameters of approximately 2,5 nm).

Temperature has little effect on the radius of pores that will empty, i.e virtually irrespective of temperature, all pores of a given size (and above) will be emptied by evaporation.

2.6.3.2.1. The influence of pore relative humidity on the porosity of HCP

As the pore relative humidity in concrete drops from 100% to 80%, theoretically almost the entire capillary porosity is emptied by evaporation. Additionally, the rate of cement hydration decreases markedly with small reductions in internal relative humidity. At 90% PRH the hydration rate is approximately half of the rate in a saturated state. On the other hand, it was observed by other researchers that no reduction in porosity took place below 95% PRH. The exposure time required, at any concrete depth, for the pore relative humidity to decrease to 95%, can therefore be considered as additional curing time.

2.6.3.2.2. The rate of evaporation

The influence of temperature and relative humidity

While the pore relative humidity and temperature governs the *pore sizes* from which evaporation occurs, these effects also determine the *rate of evaporation* of the pore water. In other words, capillaries larger than the size governed by these effects, also empty at faster or slower rates, depending on the severity of their neighbouring environment. The influence of relative humidity on the rate of evaporation increases with increasing temperature, and the influence of temperature increases with decreasing relative humidity.

The rate of evaporation decreases as soon as the pore relative humidity drops below 100%, as determined by the pore structure of the concrete. The smaller the pores, the larger the surface tension forces generated and the slower the rate of evaporation. In other words, the rate of evaporation is influenced firstly by the severity of the surrounding environment, and secondly on the properties of the concrete, as determined primarily by w:c ratio, period of wet curing and binder type.

High temperatures increase hydration as well as evaporation. Therefore the concrete can either benefit or develop poor durability properties at elevated temperatures, depending on the severity of the environment and the ability of the concrete to retain its moisture. The latter depends on the inherent microstructure of the cement paste and improves with lower w:c ratios and longer periods of wet curing.

2.7. Scope of the project

2.7.1. Environmental factors and durability

In the previous sections it has been shown that various factors influence the number, size and continuity of pores in concrete. It is known that wet curing for a sufficient duration is important in achieving durable concrete. There is also evidence that the environmental conditions during the post-curing phase, is also important.

Of these there is some useful evidence on the effects of relative humidity, but very little information on temperature and wind speed. This project was initiated to provide additional experimental data for these effects.

2.7.2. The determination of potential durability

The development of the three durability index tests has provided a useful tool with which to quantify the qualities of hardened concrete, which may potentially influence durability.

As indicated above, the post-curing environment influences the development of the properties that determine the potential durability of the concrete. The index tests were thus utilised in this project to establish relationships between potential durability and post-curing environmental conditions.

3. EXPERIMENTAL SETUP

The materials, samples and equipment used during this investigation are discussed in this chapter. This includes details concerning the cement and aggregates and the nature and amount of samples needed. Also included is a description of the chambers used to maintain stable environmental conditions, as well as the planned drying regimes.

3.1. Materials

3.1.1. Cement

The cement type used was CEM1-42,5. All the cement for the project was bagged within half an hour at the cement factory, assuring a consistent chemical composition. The oxide and clinker analyses (supplied by the factory) are given in Tables 3-1 and 3-2.

Table 3-1: Oxide analysis of the cement used for the project

Chemical constituent	Percentage
SiO_2	22.11
Al_2O_3	3.94
Fe_2O_3	4.29
Mn_2O_3	0.12
TiO_2	0.19
CaO	65.66
MgO	0.71
P_2O_5	0.14
SO_3	2.14
K_2O	0.51
Na_2O	0.19

Table 3-2: Clinker analysis of the cement used for the project

Clinker component	Percentage
C_3S	59.90
C_2S	18.37
C_3A	3.27
C_4AF	13.05
Lost on ignition	2.18
Surface area	2900

3.1.2. Aggregates

Aggregates were 19 mm Greywacke stone and Klipheuwel sand. These materials provide concrete with good workability and consistent concrete strengths.

The sieve analysis of the Klipheuwel sand is given in Table 3-3 and the grading shown in Figure 3-1. All the sand was purchased at the same time and the sieve analysis was performed according to the SABS Method 829:1976. The individual sieve analyses are given in Appendix A.

Also shown in Figure 3-2 are the SABS 1083-1976 limits, as well as preferred grading envelopes suggested by Addis [1994]. The grading of the Klipheuwel sand correlated well with the finer margin suggested by Addis [1994], and fell within or close to the SABS specification. The sand was well-graded and provided good workability of fresh concrete, without excessive bleeding and segregation of coarse aggregates.

Table 3-3: Sieve analysis of Klipheuwel sand

Sieve Aperture (mm)	Retained mass (g)	Percentage retained	Cumulative percentage retained	Cumulative percentage passing
4,750	0,0	0,0	0,0	100,0
2,360	5,0	0,5	0,5	99,5
1,180	60,0	5,8	6,3	93,7
0,600	373,3	36,1	42,4	57,6
0,300	238,3	23,1	65,5	34,5
0,150	193,3	18,7	84,2	15,8
0,075	121,7	11,9	96,1	3,9
< 0,075	40,0	3,9	100,0	0,0
Total	1031,7			
Fineness Modulus			**1,99**	

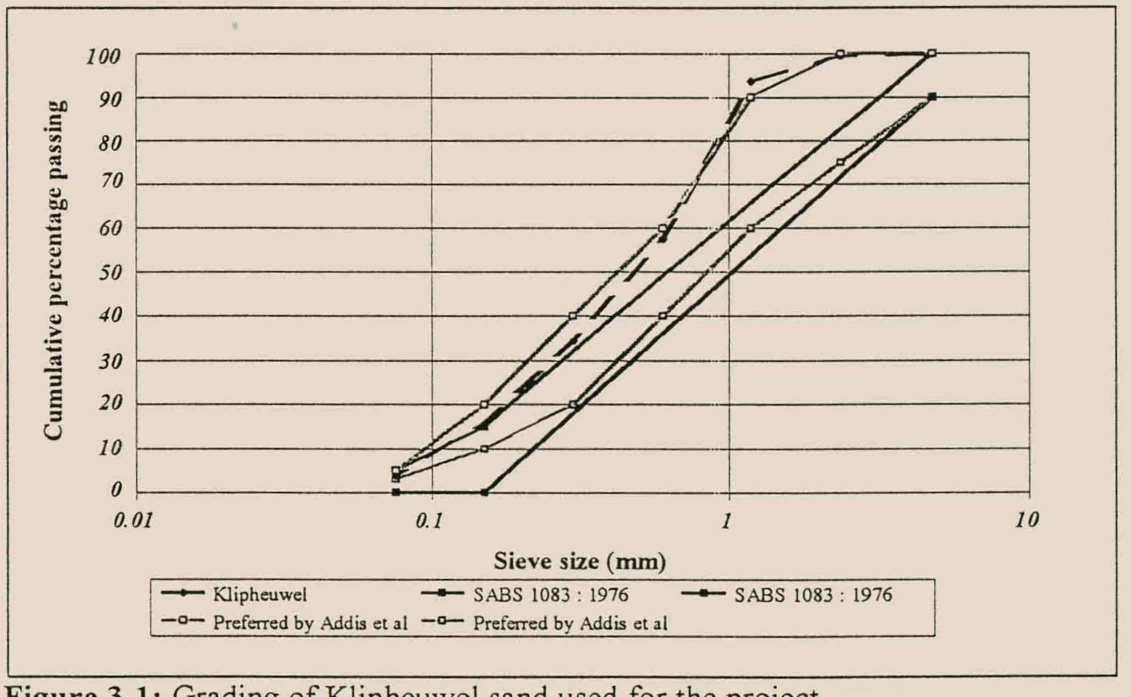


Figure 3-1: Grading of Klipheuwel sand used for the project

3.2. Concrete samples

3.2.1. Uni-directional drying

Concrete was cast in aluminium baking trays in order to allow drying in only one direction and to simulate slab-type construction (Figure 3-2). The volume of these trays was 950 ml and their dimensions 200x95x50 mm.

A wet-to-dry solvent-free epoxy was used to prevent evaporation from the sides of the concrete. The epoxy also prevented any reaction between the concrete and the aluminium.

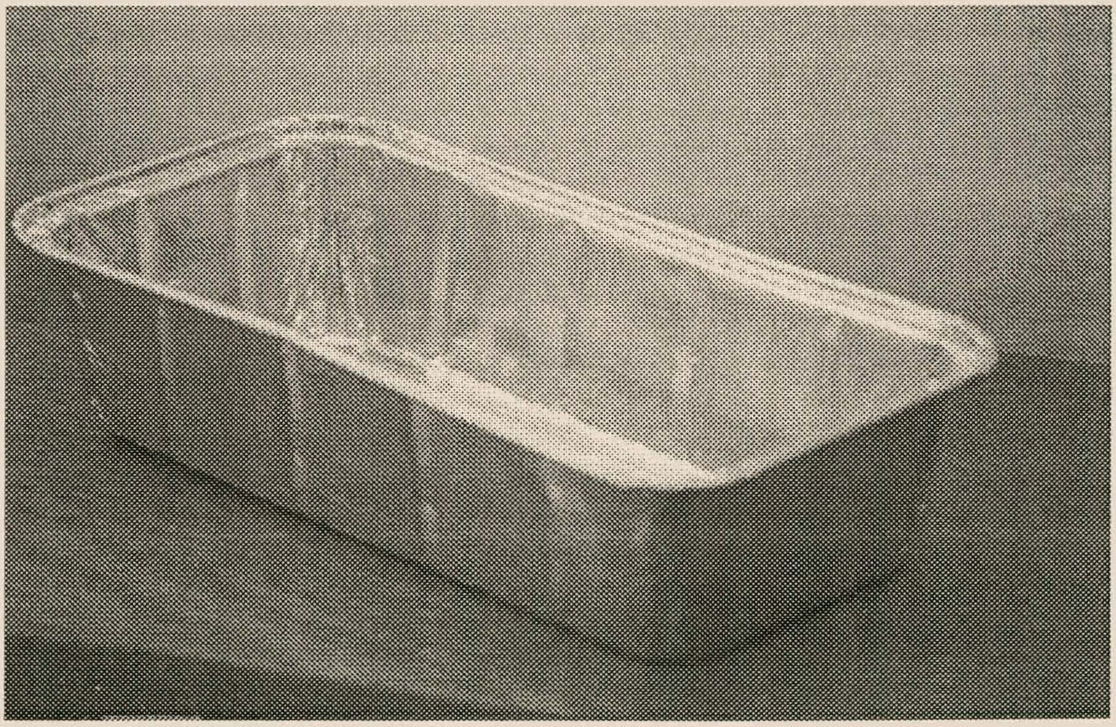


Figure 3-2: Aluminium baking trays used for experiments

3.2.2. Number of samples

In order to conduct a complete set of durability index tests, a set of at least eight core slices is needed. Four cores are used firstly to conduct the oxygen permeability test and afterwards the water sorptivity test. The other four core slices are used for the chloride conductivity test. The cores were 68 ± 1 mm in diameter and 25 mm ± 1 mm in thickness, in accordance with the test specifications of the durability index tests [Bouwer, 1998].

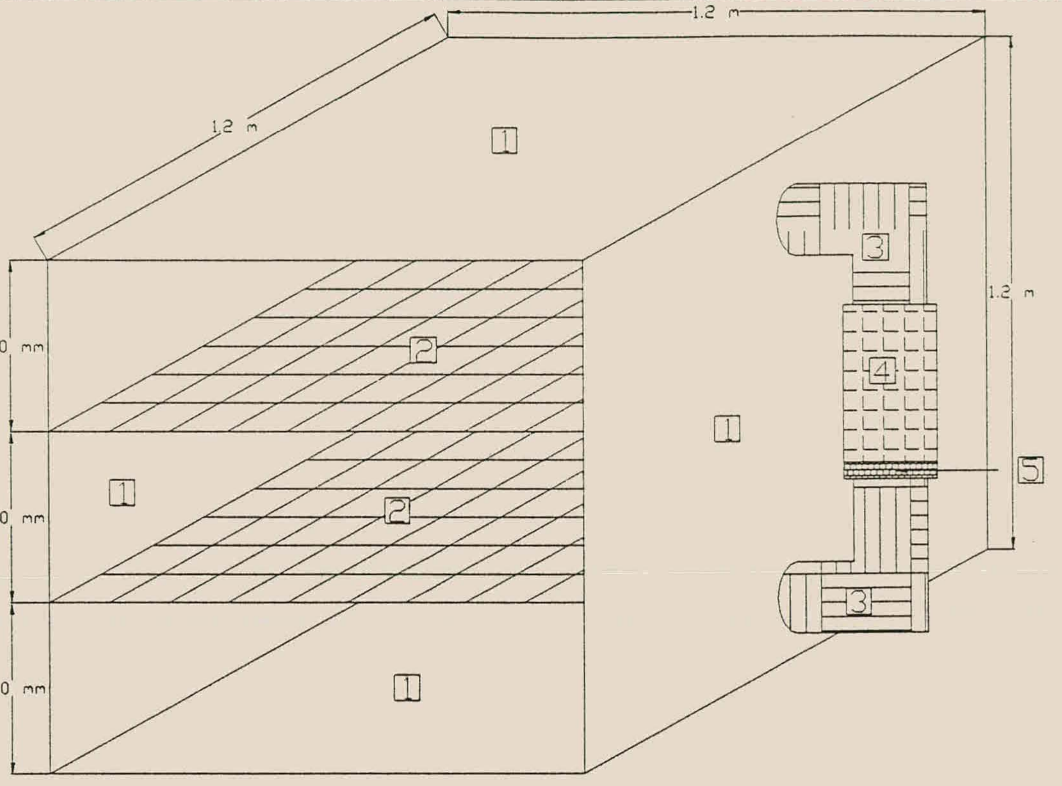
For this project four complete sets of core slices (8 cores per set) were required (for each concrete grade) after each environment was successfully simulated. From each aluminium tray two core slices could be retrieved. This meant that at least sixteen trays had to be cast for each concrete grade. Due to breakages during coring, 20 trays were made for each grade.

3.3. Simulation of environmental conditions

3.3.1. Environmental chambers

In order to obtain reliable information from the experiments conducted during this investigation, it was necessary to achieve, maintain and monitor the governing variables of the investigation for each drying regime.

Environmental chambers were built in which temperature and relative humidity could be controlled (Figures 3-3 and 3-4). The chambers were cubic of side 1,2 m and made of galvanised steel frames, 6 mm PVC sheets and polystyrene insulation.



1 - 6 mm PVC sheets, supported by a galvanised steel frame and covered with polystyrene for insulation

2 - Galvanised steel grids to support samples and trays containing saturated salt solutions

3 - Metal ducting

4 - Heating element inside the metal ducting, regulated by a thermocouple inside the chamber and a digital temperature controller

5 - Ballbearing duct fan, insulated against heat transfer from the heating element and designed to run continuously

Figure 3-3: Illustration of the environmental chambers

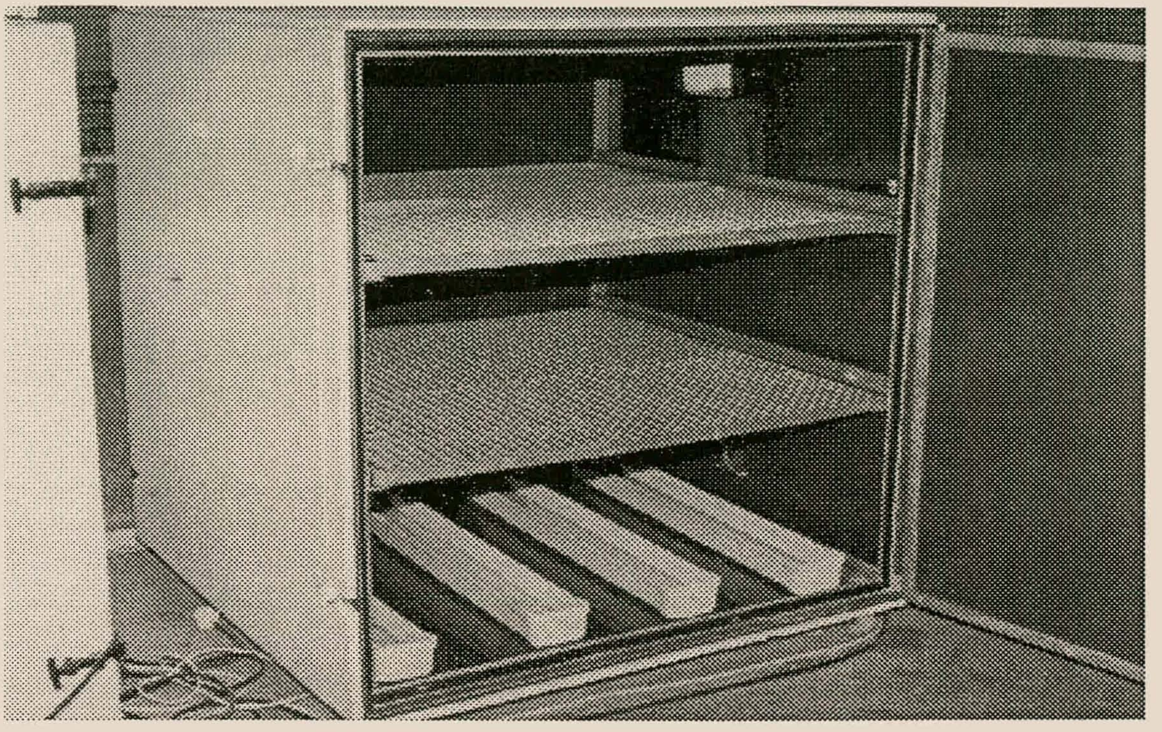


Figure 3-4: Photograph of an environmental chamber

Ducting on the outside of the chamber was used to house a 2 kW heating element and a duct fan for air circulation and temperature control (Figure 3-5). The temperature was controlled with an on/off regulation mechanism. A baffle was installed at the air inlet to distribute the incoming air properly and to prevent the creation of any significant wind speed (Figure 3-6).

The chambers were covered with polystyrene for insulation. Proper sealing of the doors and connections was insured with the use of soft rubber linings and domestic silicone. The concrete samples were placed on two galvanised steel grids.

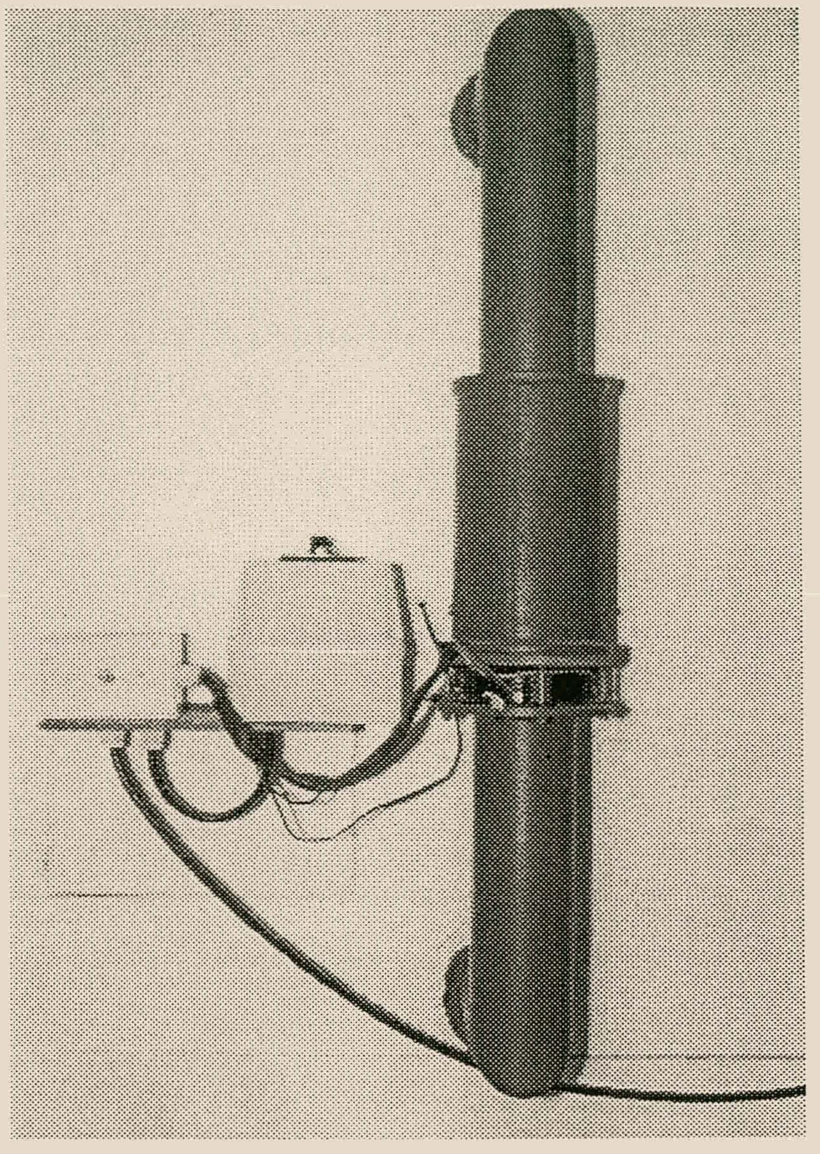


Figure 3-5: Temperature control arrangement of the environmental chambers

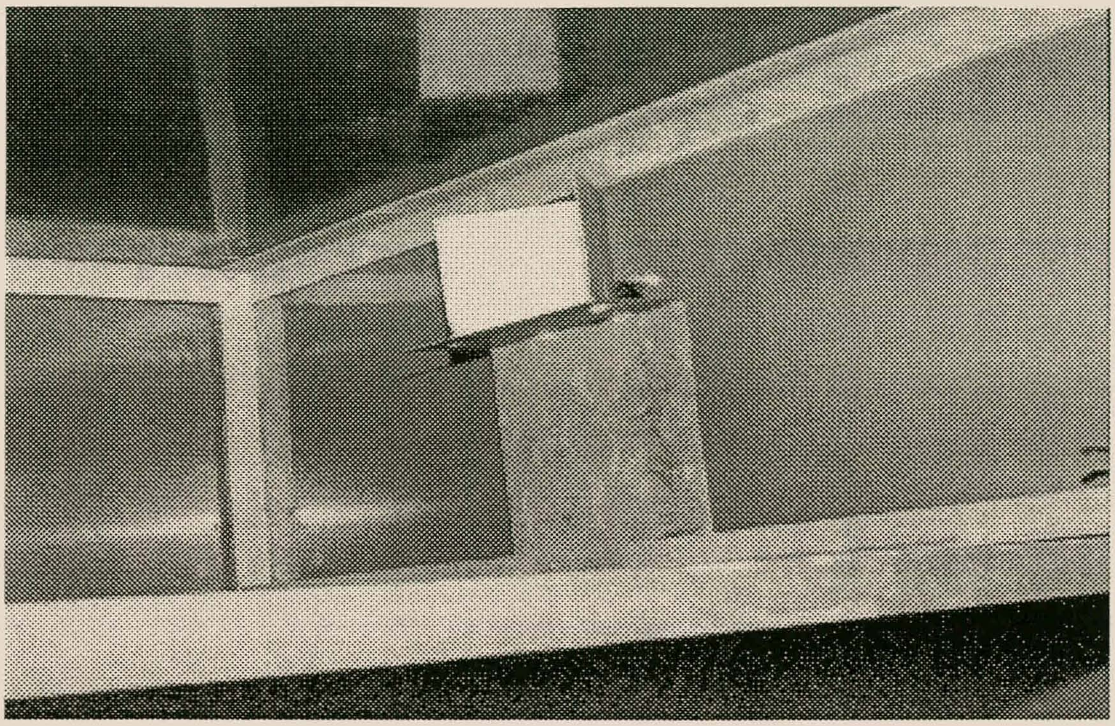


Figure 3-6: Baffle at the air inlet for distribution of air inside the chamber

3.3.2. Temperature room

While relatively warm temperatures (above 25°C) could be maintained in the environmental chambers, they were not supplied with air cooling apparatus (because of excessive costs). Because of this the experiments done at 20°C had to be conducted in closed cabinets in an air-conditioned room.

These cabinets were smaller than the environmental chambers (1500 x 500 x 1000 mm) and samples were placed on two galvanised steel grids. Since they were placed inside a room that remained at a constant temperature, temperature differentials were not expected and they were not provided with any means of air circulation.

3.3.3. Control of relative humidity

The relative humidity was controlled with the use of saturated salt solutions. These were kept in 6 to 8 gutter-shaped plastic trays in the bottom of the chambers and cabinets. The dimensions of these trays were 1000x55x 65 mm. The relative humidity could be increased or decreased by adding trays with water or dry salt respectively. The salts used to maintain the desired relative humidities of this investigation are given in section 3.3.5.

3.3.4. Monitoring of environmental conditions

Measuring of temperature and humidity inside the environmental chambers and cabinets in the temperature room was done with the aid of an electronic hygrometer. The instrument was calibrated by the suppliers before delivery. Its accuracy was checked once a week against a wet-and-dry bulb thermometer. A probe was connected to the instrument and inserted into the chambers and cabinets at different monitoring points.

3.3.1.1. Environmental chambers

The conditions in the chambers were initially monitored at five different points. These were located as illustrated in Figure 3-7. Point number 5 was located on the same panel as the temperature controller, with points 1 to 4 on the opposite panel. It was found that point number 3 reflected the average of the five monitoring points, and was used during the experimental phase of this project.

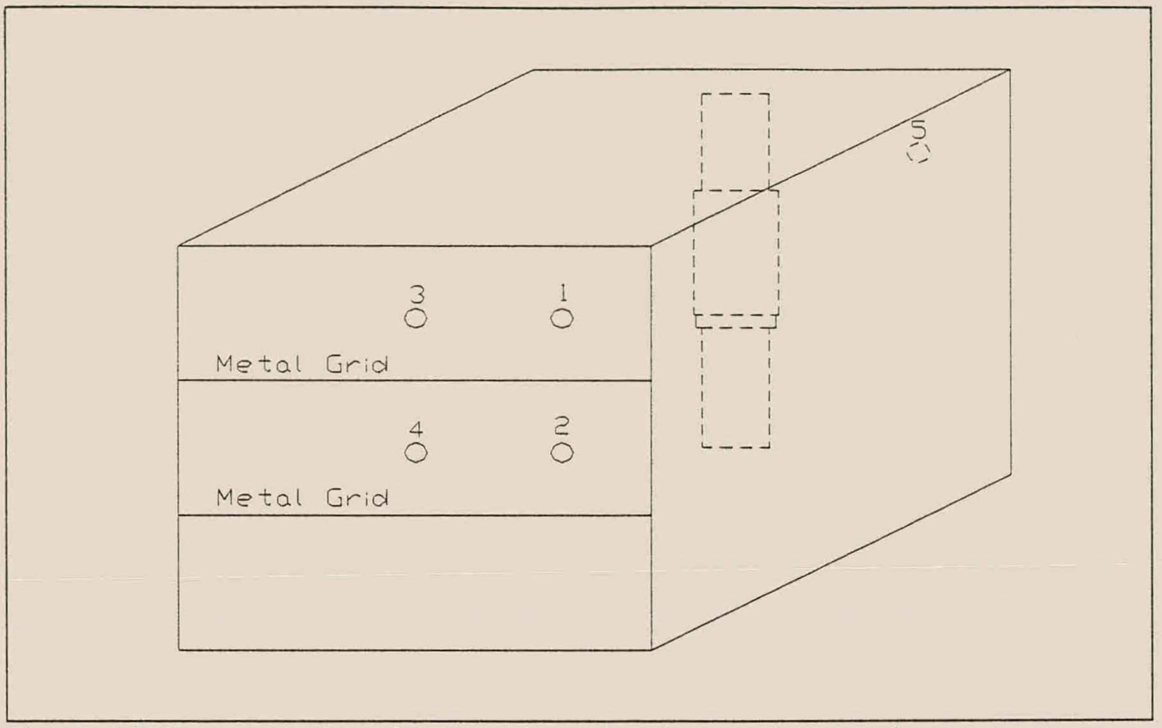


Figure 3-7: Location of monitoring points of environmental chamber

The method of temperature control resulted in cyclic changes of conditions inside the chambers. The heating element remained off until the temperature inside the chamber reduced to a value lower than the setting on the control unit. The heating element was then activated, and resulted in a rapid increase in temperature. The control unit de-activated the heating element when the temperature had risen to approximately 2°C higher than the setting. The temperature inside the chamber still rose slightly (typically with 1°C), before it started cooling down again.

The rate at which conditions cooled down, depended on the relative temperature difference in- and outside of the chamber. At high temperature settings, there was rather rapid cooling down of the temperature inside the chamber. At cooler settings, the decrease in inside temperature was more gradual.

The fluctuations in temperature also resulted in fluctuations of relative humidity. Higher temperatures were accompanied by lower relative humidities, and vice versa. The magnitude of fluctuations in relative humidity was typically 6% to 8%.

The probe for the temperature controller was located at point number 5. It was found that the temperature reading of the temperature controller differed from the one taken with the electronic hygrometer, meaning that the controller wasn't properly calibrated. The temperature setting on the controller was adjusted on a trial-and-error basis until the required temperature inside the chamber was achieved.

3.3.1.2. Cabinets in the temperature controlled room

The cabinets in the temperature room were relatively small (volume = 0.75 m^3) and conditions were monitored via a single monitoring point. This point was located in the middle of the cabinet doors, halfway between the top of the cabinet and the first galvanised grid.

3.3.5. Environmental conditions simulated

The main concern of this investigation was to determine the influences of temperature and relative humidity on potential concrete durability, since it was expected that they would have the most prominent effects on concrete drying. A trial assessment was done on the influence of wind speed, the procedure of which is discussed in section 4.6.1.

The details of the simulated environmental conditions (in terms of temperature and relative humidity), together with the appropriate salt solutions used, are summarised in Table 3-3. These environmental conditions were chosen in order to simulate typical construction situations in South Africa, which is in general a country of moderate to warm climate.

Table 3-3: Environmental conditions simulated

Environ-ment	Relative Humidity (%)	Temp. (°C)	Wind speed (m/s)	Salt used to control relative humidity
1	100	20	0	Water bath
2	50	35	0	NH_4NO_3
3	50	27,5	0	$Ca(NO_3)_2.4H_2O$
4	50	20	0	$Na_2Cr_2O_7.H_2O$
5	65	20	0	NH_4NO_3
6	80	20	0	NaCl
7	60	20	5,6	N/A*

* This experiment was conducted in a temperature controlled room, with moderate relative humidity control.

4. EXPERIMENTAL PROCEDURES AND TEST METHODS

The procedure followed to obtain the necessary experimental data for this project is illustrated in Figure 4-1, followed by a brief summary of the various stages.

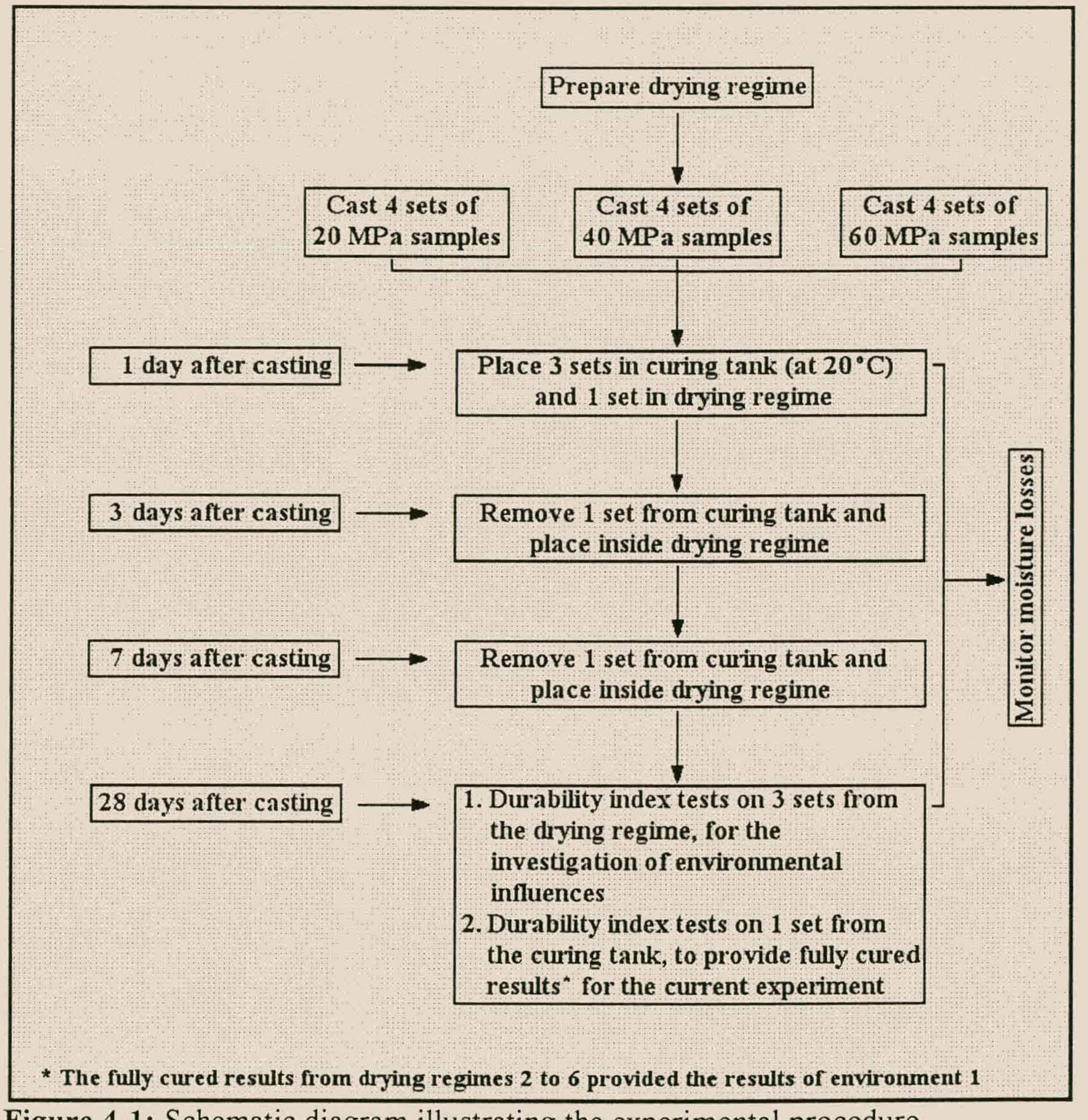


Figure 4-1: Schematic diagram illustrating the experimental procedure

- A drying regime of constant temperature, relative humidity and wind speed was prepared. This regime would provide controlled environmental conditions during the drying period of newly cast concrete samples. Altogether six various drying regimes were investigated (excluding fully wet cured conditions), the details of which are discussed in Chapter 5.

- OPC concretes of three different grades (20, 40 and 60 MPa) were cast in aluminium baking trays, to allow uni-directional drying. Enough samples were cast to be able to conduct four complete sets of durability index tests for each concrete grade.
- One set of samples (for each grade) was wet cured for 1 day before placing it in the drying regime. Two more sets were wet cured for 3 and 7 days respectively before the start of exposure, while the last set was wet cured for 28 days after casting (at 20 ± 2°C) to provide fully cured results for each batch of concrete investigated.
- Weight measurements of each set of samples were taken once a day, for 7 days after the start of exposure. A final weight measurement was taken at the end of the drying period.
- At 28 days after casting, all concrete samples were cored and subjected to the durability index tests.
- The compressive strength of the concretes investigated was monitored at 28 days, for each of the drying regimes investigated.

The details concerning the experimental procedure of this project are discussed subsequently. This includes the manufacturing, conditioning and testing procedures.

4.1. Concrete mixes and manufacturing procedures

Only OPC concretes were investigated. It was decided to use target strengths of 20, 40 and 60 MPa in order to compare results with work already done in the overall research programme on concrete durability [Alexander, 1997; Ballim, 1993; Bouwer, 1998; Streicher, 1996].

4.1.1. Mix designs

The water content of the fresh mixes had to be kept consistent throughout the experimental phase. For consistent workability (a slump of 50 ± 10 mm) for all three mixes, the water content used were 180, 185 and 195 litres/m^3 for the 20, 40 and 60 MPa concretes respectively. The mix properties for the three concrete strengths are given in Table 4-1. The slumps indicated (done in accordance with the Draft SABS Method 862, Part-I) are the averages of all the concrete batches cast during the project, and varied between 30 mm and 60 mm. These are given in Appendix B, together with the compressive strengths of all the batches of concrete investigated.

Table 4-1: Mix designs

	Mix proportions per m^3		
	20 MPa	**40 MPa**	**60 MPa**
W/C	0,84	0,56	0,40
Water (kg)	180	185	195
Cement (kg)	214	330	488
Stone (kg)	1050	1050	1050
Sand (kg)	942	831	672
		Lab. mix (0,025m^3)	
Water (kg)	4,55	4,68	4,93
Cement (kg)	5,42	8,36	12,33
Stone (kg)	26,56	26,56	26,56
Sand (kg)	23,84	21,02	17,00
Slump (mm)	40	45	50

4.1.2. Casting

Concrete was mixed for the three respective strength grades (20, 40 and 60 MPa) on three consecutive days. A pan mixer was used, of which the pan and blades were wiped down with a wet cloth prior to mixing. This was done in order to avoid absorption of mixing water and consequently influencing the water content of the fresh concrete.

The mix was dry-mixed for thirty seconds, after which the mixing water was added over approximately another thirty seconds. A standard slump test was taken [SABS 0100-1 & 2: 1992] after approximately two minutes of mixing. The concrete was mixed again afterwards and cast into the aluminium baking trays, which were pre-coated with the wet-to-dry solvent-free epoxy.

Compacting was done on a vibrating table and the fresh batch of trays was covered with plastic for twenty four hours after casting. They were left in the laboratory at 20 ± 3°C. From each batch of concrete, three cubes were cast for 28 day strength checks.

4.1.3. Curing

At one day after casting, five trays were cleaned of all loose concrete that could influence weight measurements, weighed and placed inside the appropriate drying regime. The rest of the trays and the cubes were placed inside a curing tank. The temperature of this tank was kept as close to 20°C as possible.

At 3 days after casting, five more trays were cleaned, weighed and placed inside the environment. This procedure was repeated again 7 days after casting and the final five trays were left in the tank for the full period of 28 days after casting.

4.2. Monitoring and preparation of test samples

4.2.1. Weight measurements

Each aluminium tray was weighed once a day for 7 days after removal from the curing tank and placement inside the drying regime. A final weight measurement was taken at 28 days, just before coring and slicing. The average weight loss of each set of five trays was calculated and plotted. The results of these measurements are given and discussed in Chapter 6.

4.2.2. Coring and slicing

Twenty eight days after casting, all aluminium trays were removed from the drying regime and curing tank and cored and sliced. From each tray, two cores of approximately 68 mm diameter were retrieved. From the drying face of the core 5 mm was sliced off. The core was then sliced to a thickness of 25 ± 1 mm. These cores were placed inside an oven maintaining a temperature of 50°C as final preparation for the conducting of the durability index tests.

It proved difficult to retrieve cores suitable for testing in the case of the 20 MPa concrete, especially in cases where little wet curing was applied. When some of these cores were retrieved the aggregates tended to come loose, damaging the core to such an extent that it was impossible to use for testing. Two such cores are shown in Figure 4-2. It appears that poorly cured 20 MPa concrete is the lower limit where such durability index experiments can be conducted.

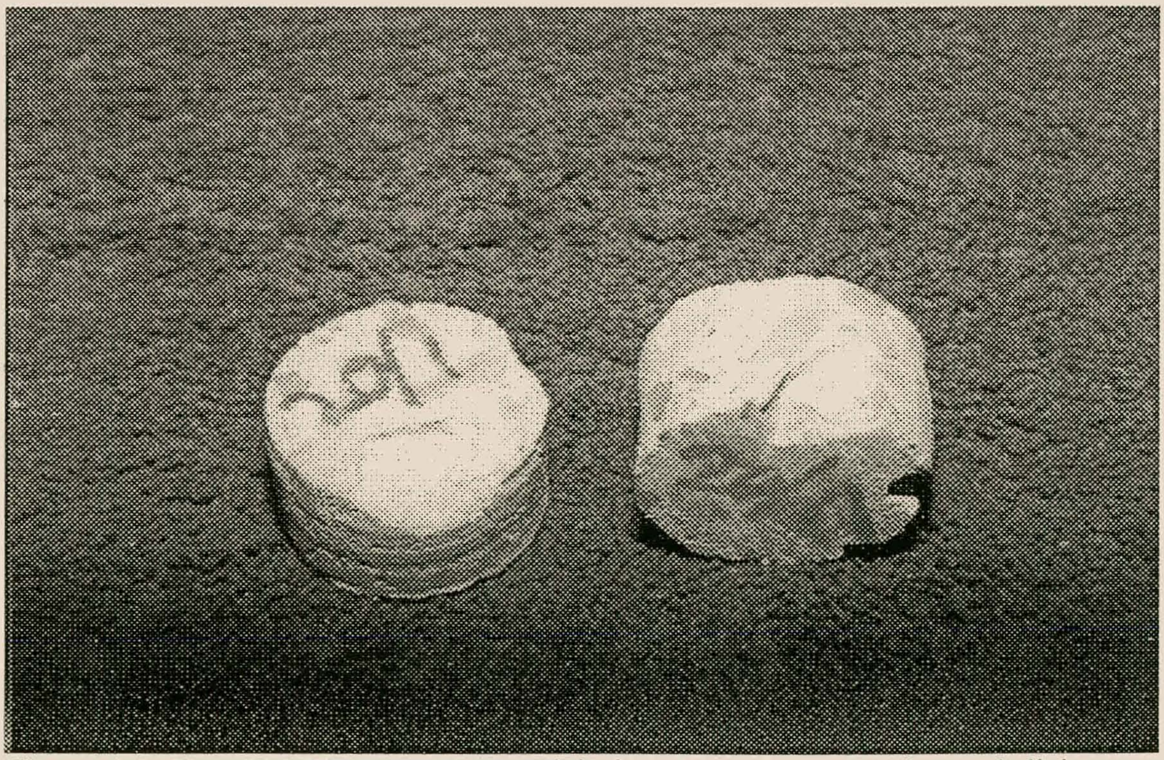


Figure 4-2: Two 20 MPa cores, damaged during the process of coring and slicing

4.3. Durability index tests

Cores were removed from the oven when the mass change over 24 hours were less than 0,1%, and subjected to the durability index tests. These are the chloride conductivity, oxygen permeability and water sorptivity.

4.4. Compressive strength measurements

The compressive strength of all concrete mixes were monitored 28 days after casting, in accordance with the SABS Method 863 test specification [SABS 0100-1 & 2: 1992]. The details of the compressive strengths obtained are given in Appendix B.

4.5. Environmental stability

It was found that the temperature in the environmental chambers fluctuated over a range of 3 to 4°C, allowing control of an average temperature with ± 1,5 to 2°C. In the temperature room the temperature inside the cabinets remained constant within 1°C. During the investigations of environments 4 and 6, the control unit failed and resulted in increases in temperature of approximately 1 to 2,5°C before the situation was brought under control.

The relative humidity in the environmental chambers fluctuated over a range of 6 to 8 percentage points, allowing an average with ± 3 to 4 percentage points. Maximum temperatures were accompanied by minimum relative humidities and vice versa.

The relative humidity was affected when wet samples were added, and had to be reduced by adding dry salt. This was also the case in the closed cabinets in the temperature room. As a result, fluctuations of varying magnitude in relative humidity were experienced in some environments.

These fluctuations, together with the increased temperatures during failure of the control unit in the temperature room, are discussed in Chapter 5. The influence thereof on experimental results are discussed in Chapters 6 and 7.

4.6. Secondary investigations

4.6.1. Preliminary assessment of the influence of wind speed

Tests were run on samples of concrete of low potential durability (target strength of 20 MPa and one day wet curing) and on better quality concrete (40 MPa, 7 days wet cured) to determine whether wind speed had any significant effect on potential durability.

For the 20 MPa concrete, eight aluminium trays were cast according to the procedure described in section 4.1.2. The samples were covered with plastic for 24 hours and then cleaned of loose pieces of concrete that could influence weight losses. They were left until they were surface-dry, weighed and placed inside a room with a stable environment in terms of temperature and relative humidity. These were monitored on a daily basis. The same amount of samples were cast for the 40 MPa concrete. These were wet cured for 7 days (covered for 24 hours and wet cured for 6 days) and conditioned in a similar manner.

Four of the samples were left in still air and the other four underneath a fan. The average wind speed generated by the fan was measured with a wind anemometer.

The concrete samples were weighed on a daily basis to determine whether there was any significant differences in moisture losses from the two groups of samples. This procedure was followed until differences between successive moisture losses were negligible (less than 0,1%). They were then cored and sliced according to the procedure described in section 4.2.2 and subjected to the durability index tests. The results of this investigation are given in Chapters 6 and 7.

4.6.2. The influence of the direction of casting

In the standard preparation of cores for the durability index tests, cubes are cored perpendicular to the direction of casting. During this investigation, all coring was done parallel to the direction of casting. The influence of this difference was investigated by casting extra cubes while simulating environments 3, 4 and 5. They were wet cured for 28 days, cored according to standard procedures and subjected to the durability index tests. The results of this investigation are given in Chapter 7.

5. ENVIRONMENTAL CONDITIONS OF THE DRYING REGIMES

Maintaining constant and stable environmental conditions in terms of temperature, relative humidity and wind speed was a very important part of this investigation. Each drying regime proved to be unique in terms of overall behaviour and is discussed individually.

5.1. Comparing the relative influences of temperature and relative humidity on the severity of exposure conditions

Before the environmental conditions of the different drying regimes are discussed, the method by which they will be illustrated must be justified. The problem lies in comparing fluctuations in temperature with fluctuations in relative humidity. A fluctuation of 1°C in temperature will have the same effect on the severity of drying conditions as a certain fluctuation in relative humidity. If these two factors are represented on the same plot (to illustrate the magnitude of fluctuations) this relationship must be quantified.

By describing the severity of drying conditions in terms of the rate of evaporation of free surface water (E), a relationship can be established between the effects of temperature and relative humidity (see section 2.3.3.2.1). This relationship is given by:

$$RH = -20{,}702\left[\frac{E - 4{,}831 \cdot 10^{-2} e^{\frac{17{,}3T}{237{,}3+T}}}{e^{\frac{17{,}3T}{237{,}3+T}}}\right] \tag{5-1}$$

where E = rate of evaporation (kg/m^2/hr)

RH = ambient relative humidity (% / 100)

T = ambient temperature (°C)

According to equation 5-1, the relationship between RH and T vary with different rates of evaporation. In Table 5-1, the values of E for the different drying regimes are given (see Figure 2-17). Also shown, is the relative humidity fluctuation (in each drying regime) which will have the same effect on the rate of evaporation as a fluctuation of 1°C in temperature. An example calculation is shown to clarify the values obtained:

Given:

E = 0,223 kg/m^2/hr (environment 2)

T = 34, 35 and 36°C

Calculation of RH:

RH (34) = 47,2%

RH (35) = 50,0%

RH (36) = 52,7%

RH (35) - RH (34) = 2,8%

RH (36) - RH (35) = 2,7%

Thus the average equivalent fluctuation in relative humidity (for a fluctuation of 1 °C in temperature) is equal to:

(2,8% + 2,7%) / 2 = 2,75%

Using this information, the conditions in the drying regimes can be sensibly illustrated, i.e. the scales of the axes can be set to illustrate the relative order of magnitude of both temperature and relative humidity fluctuations.

Table 5-1: The fluctuation in relative humidity equivalent to a fluctuation in temperature of 1°C, for environments 2 to 6

Drying regime (planned conditions)	Rate of evaporation ($kg/m^2/hr$)	Fluctuation in relative humidity approximately equivalent to a fluctuation of 1°C in temperature (%)
2 (35°C, 50% RH)	0,223	2,75
3 (27,5°C, 50% RH)	0,146	2,95
4 (20°C, 50% RH)	0,093	3,10
5 (20°C, 65% RH)	0,065	2,15
6 (20°C, 80% RH)	0,037	1,20

5.2. Environment 1 - 20°C, fully wet cured

This was the 'reference' or 'fully cured' environment, and was achieved by placing concrete samples in a curing tank for 28 days after casting. The temperature inside this curing tank remained at 20 ± 2°C throughout the investigation.

For each of environments 2 to 6, extra sets of 20, 40 and 60 MPa samples were cast and placed inside the curing tank for the entire curing period, while the other samples were placed inside the different drying regimes. At 28 days after casting, these fully cured samples were tested together with the rest of the samples. The index results obtained from these fully wet cured samples (given in Chapter 7) were considered to characterise the optimum potential durability that could be achieved by the three concrete grades under consideration.

5.3. Environment 2 - 35°C, 50% relative humidity

This drying regime aimed at an average of 35°C and a relative humidity of 50%, controlled by using saturated solutions of NH_4NO_3. The simulation was conducted in an environmental chamber, resulting in cyclic changes in temperature and relative humidity (see section 3.3.1.1).

In Figure 5-1 a typical time cycle is shown, with the Y_1 and Y_2 axes set to the relationship given in Table 5-1 (i.e. 1°C = 2,75% RH). It can be seen that the temperature and relative humidity fluctuations have almost equal influences on drying conditions, as can expected in a sealed environment.

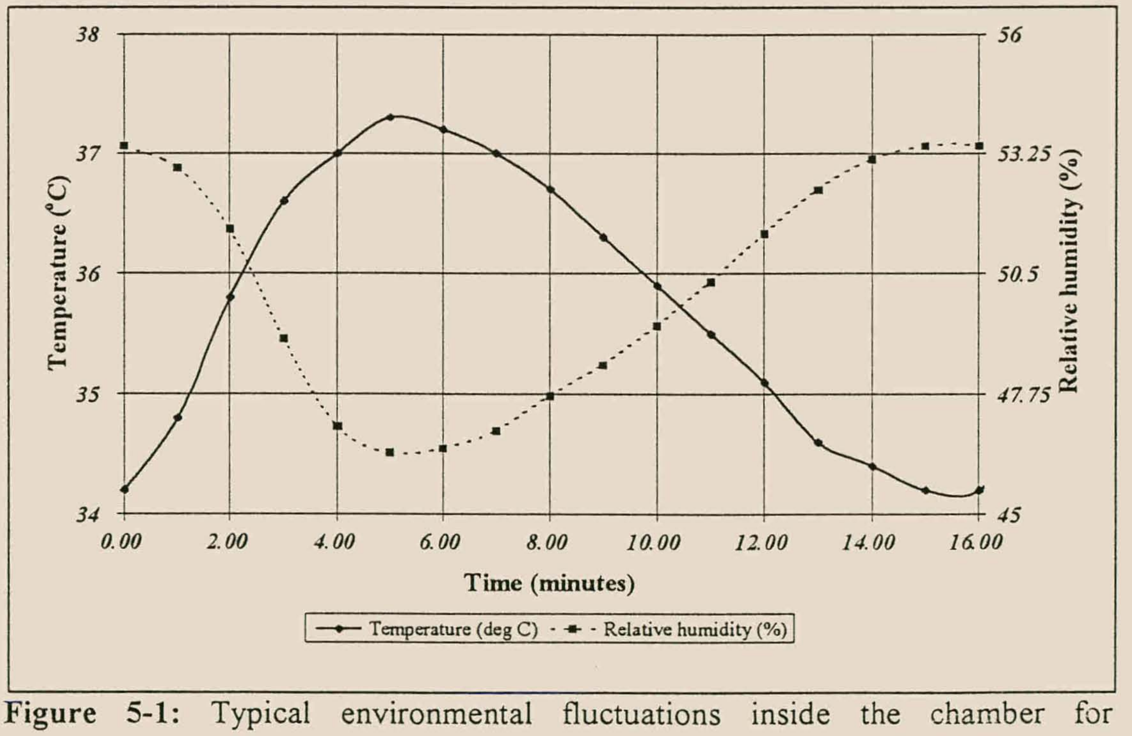


Figure 5-1: Typical environmental fluctuations inside the chamber for environment 2, simulating a temperature of 35°C and a relative humidity of 50%

The temperature typically rose from a minimum (33 to 34°C) to a maximum value (36 to 38°C) in 3 to 5 minutes during the air heating cycle, and reduced again to the minimum value in 10 to 12 minutes. Minimum temperatures were accompanied by maximum relative humidities in the range of 53% to 61%. The minimum relative humidities, accompanying maximum temperatures, varied between 43% and 51%. The swift decrease in temperature was a result of the high temperatures inside the chamber, relative to the temperature in the laboratory.

In order to calculate the true averages of the temperature and humidity during such a cycle, one would have to integrate the curves in order to obtain the areas underneath them. However, because of the shape of the curves, the averages of the minimum and maximum temperatures and relative humidities were sufficiently accurate. As an example, the average of the temperature of Figure 5-1 was calculated using a graphical analysis and yielded 35,3°C, in comparison with 35,7°C when the average of the minimum and maximum temperatures was used.

The chamber had to be opened once a day (for approximately half an hour) for more than two weeks after casting, to add and weigh samples. It was found that the conditions inside the chamber stabilised again within an hour after closing it. The minimum and maximum temperatures and relative humidities (of the cyclic fluctuations) remained sufficiently constant between openings, and were used to calculate daily averages. These were used to calculate the average conditions during the drying period.

The variation of minimum and maximum temperatures and the duration of heating and cooling cycles were dependent on the ambient temperature in the laboratory. The average daily humidity (in the chamber) varied as a result of the laboratory conditions when the chamber was opened and the influence of the wet samples being added.

The average daily conditions throughout the drying period are illustrated in Figure 5-2, on a scale of 1°C = 2,75% RH. Except for peaks in relative humidity on days

5 and 12, the order of magnitude of the temperature and relative humidity fluctuations were similar, i.e. an equivalent of approximately 4°C. In Appendix C, the laboratory measurements of all the drying regimes are given, together with the calculated daily averages.

The average temperature during the drying period was 35,3°C (to the nearest 0,1°C) with a standard deviation of 0,9°C. The average relative humidity was 51,5% (to the nearest 0,5%) with a standard deviation of 3,3%. The coefficient of variation was 2,44% in the case of temperature control and 6,31% in the case of relative humidity control.

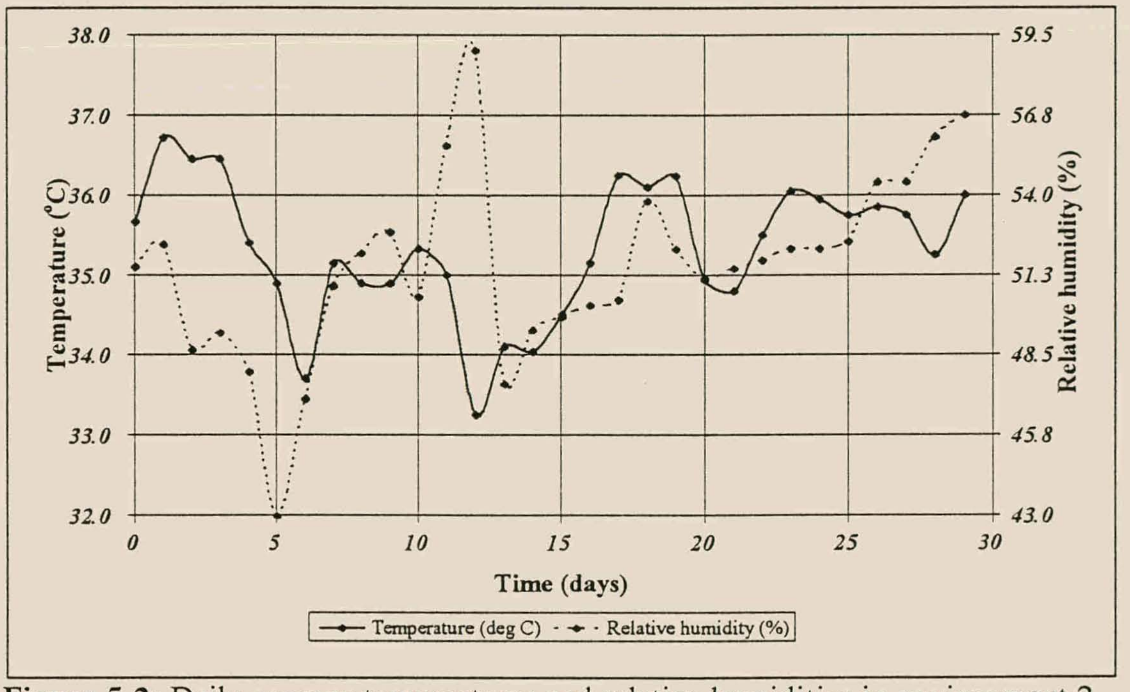


Figure 5-2: Daily average temperatures and relative humidities in environment 2

5.4. Environment 3 - 27,5°C, 50% relative humidity

This drying regime aimed at an average of 27,5°C and a relative humidity of 50%, using saturated solutions of $Ca(NO_3)_2.4H_2O$. However, it was found that $Na_2Cr_2O_7.H_2O$ was a more effective salt and was used instead. The simulation was conducted in an environmental chamber and the following fluctuations in temperature and relative humidity were noted (see Figure 5-3 for a typical cycle, on a scale of 1°C = 2,95% RH).

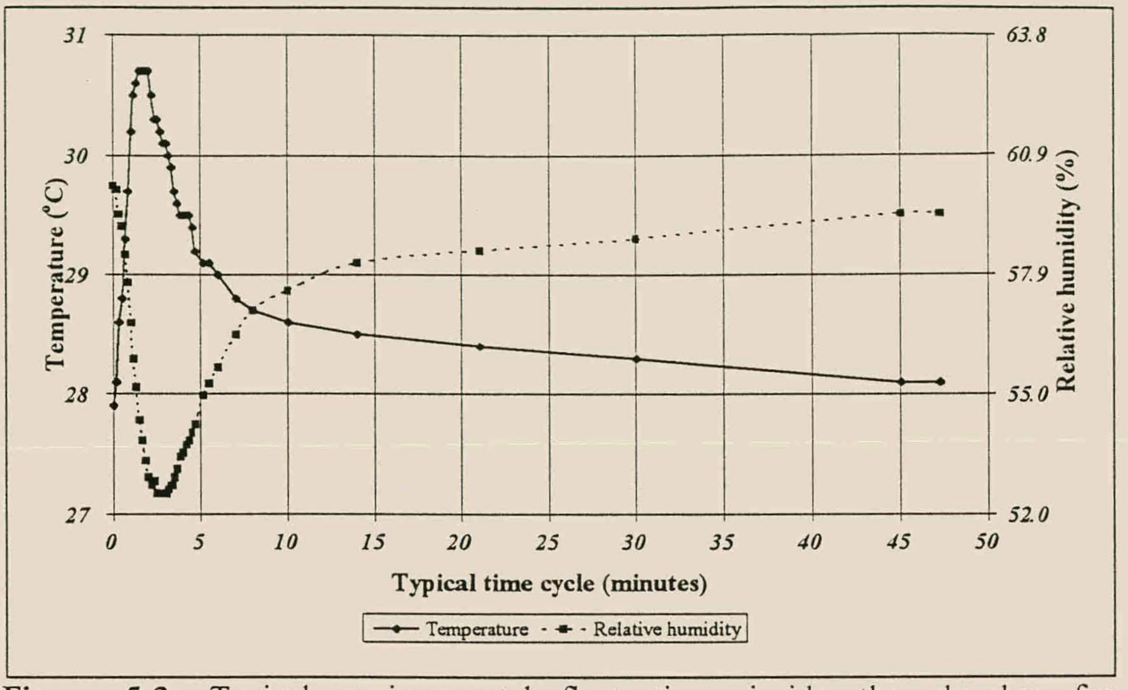


Figure 5-3: Typical environmental fluctuations inside the chamber for environment 3, simulating a temperature of 27,5°C and a relative humidity of 50%*

The temperature rose from a minimum (26,5 to 27,5°C) to a maximum value (29,5 to 31°C) in 2 to 3 minutes and descended again to the minimum value in approximately 45 minutes. Minimum temperatures were accompanied by maximum relative humidities in the range of 52% to 60%. The minimum relative humidities accompanying maximum temperatures varied between 44% and 49%. The decrease in temperature was much slower than that observed in environment 2. This was due to smaller differences in temperature between the conditions inside the chamber and those in the laboratory.

* This particular cycle was monitored on a day with high ambient temperatures and after wet samples had been added about an hour previously. This explains why both the average temperature and relative humidity were higher than 27.5°C and 50%.

In order to calculate the averages of the temperature and humidity during such a cycle, it was necessary to determine the areas underneath the curves in Figure 5-3. This was done by calculating the weighted averages over the time interval of the fluctuation. The procedure followed for calculating the average temperature of such a cycle can be summarised as follows:

- The time interval of the cycle was divided into n intervals of unequal length, representing the time intervals (t_i) at which temperature readings (T_i) were taken. This was a result of the sharp rise and gradual decrease in temperature. For example, during the first 5 minutes, while the temperature was rising, the lengths of the time intervals were short and in the order of 10 seconds. As the maximum temperature was reached and the temperature started dropping again, the time intervals between readings were stretched for longer periods, since the decrease in temperature was much more gradual than the initial rise.
- The average temperature between any two readings was equal to $(T_i+T_{i-1})/2$, while the length of the interval was equal to $(t_i - t_{i-1})$. The weighted average of the temperature over the entire cycle could be calculated from the formula:

$$T_{ave} = \frac{\sum_{i=1}^{n}\left(\frac{T_i + T_{i-1}}{2}\right)\left(t_i - t_{i-1}\right)}{t_{total}} \tag{5-2}$$

where T_{ave} = average temperature during the fluctuation

T_i and T_{i-1} = temperature readings at times t_i and t_{i-1} respectively

t_{total} = total period of the fluctuation in temperature ($= \sum t_i$)

The average relative humidity during the time interval could be calculated in a similar way from the formula:

$$RH_{ave} = \frac{\sum_{i=1}^{n}\left(\frac{RH_i + RH_{i-1}}{2}\right)(t_i - t_{i-1})}{t_{total}} \tag{5-3}$$

where RH_{ave} = average relative humidity during the fluctuation

RH_i and RH_{i-1} = relative humidity readings at times t_i and t_{i-1} respectively

t_{total} = total period of the fluctuation in relative humidity ($= \sum t_i$)

The chamber had to be opened once a day (for approximately half an hour) for more than two weeks after casting, to add and weigh samples. It was found that the conditions inside the chamber stabilised again within half an hour after closing it. The fluctuations between minimum and maximum temperatures and relative humidities remained sufficiently constant between openings, and were used to calculate daily averages. Finally, the daily averages were used to calculate the average conditions during the drying period.

The average conditions throughout the drying period are illustrated in Figure 5-4, on a scale of 1°C = 2,95% RH (see Table 5-1). The temperature and relative humidity fluctuations were relatively small during the first 15 days, and in the order of an equivalent temperature of approximately 2°C.

At this stage the relative humidity started decreasing quite significantly. This was possibly a result of very dry conditions in the laboratory at the time, as well as the fact that no more wet samples were added. Compensation was attempted by removing some of the trays of salt solutions and adding trays with clean water, the effect of which can be seen in Figure 5-4.

The overall average temperature during the drying period was 27,9°C with a standard deviation of 0,4°C. The average relative humidity was 52,5% with a standard deviation of 2,4%. The coefficient of variation was 1,32% in the case of temperature control and 2,55% for relative humidity control.

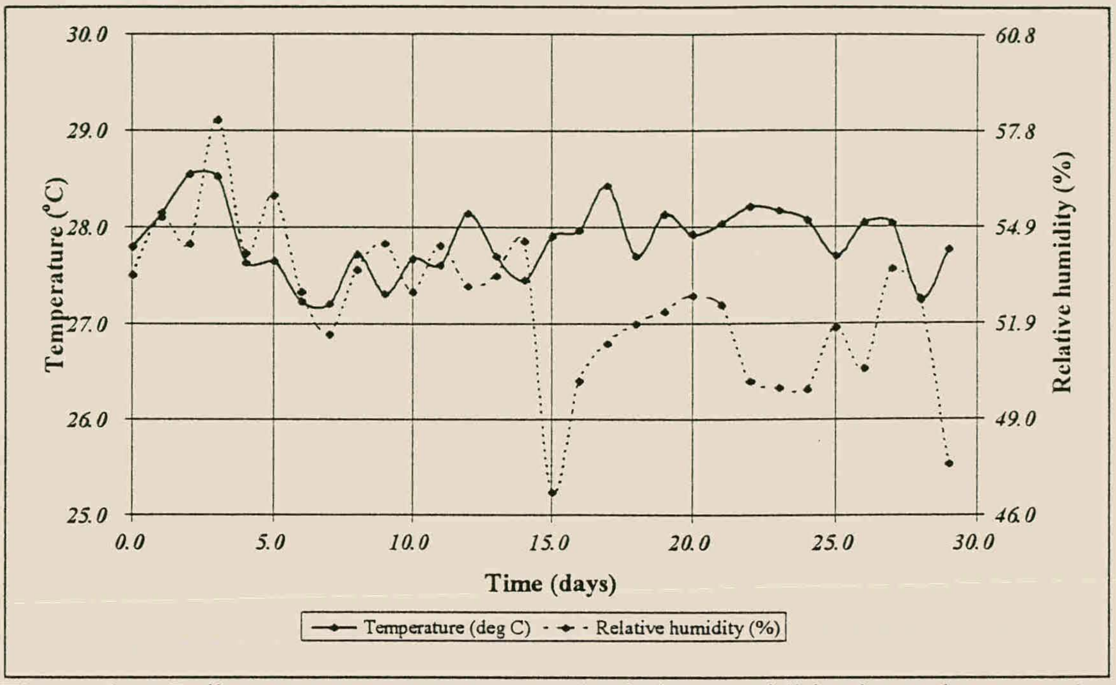


Figure 5-4: Daily average temperatures and relative humidities in environment 3

5.5. Environment 4 - 20°C, 50% relative humidity

This drying regime aimed at an average of 20°C and a relative humidity of 50%. The simulation was conducted in a room in which temperature and relative humidity could be controlled. However, at the time a problem with the relative humidity control unit was encountered and the samples were rather left to dry inside an airtight cabinet. The relative humidity in the cabinet was controlled with the use of $CaCl_2$.

The cabinet had to be opened once a day for more than two weeks after casting, to add and weigh samples. The adding of wet samples induced rises in relative humidity up to 71%, but more generally to levels in the order of 58% to 62%. Dry $CaCl_2$ was added with the wet samples and successfully reduced the humidity to $50 \pm 3\%$.

Because of the constant room temperature there were no cyclic changes in either temperature or humidity. The conditions inside the cabinet were noted on a regular basis over the full drying period. The final average temperature and relative humidity were found by using equations 5-2 and 5-3, calculating the weighted averages over the entire drying period. The average daily conditions throughout the drying period are illustrated in Figure 5-5, on a scale of 1°C = 3,10% RH.

The fluctuations in relative humidity were slightly more significant than the fluctuations in temperature, and in the order of an equivalent temperature of approximately 5°C. The temperature fluctuated over a range of approximately 3,5 °C.

There were two stages during the drying period when the temperature control unit failed, leading to rises in the room temperature. However, temperatures never exceeded 21°C before the problem was rectified. The first failure happened very early in the drying phase (4 days after casting and when some samples had just been added from the curing tank) and might have had a minor influence on the results obtained from this environment.

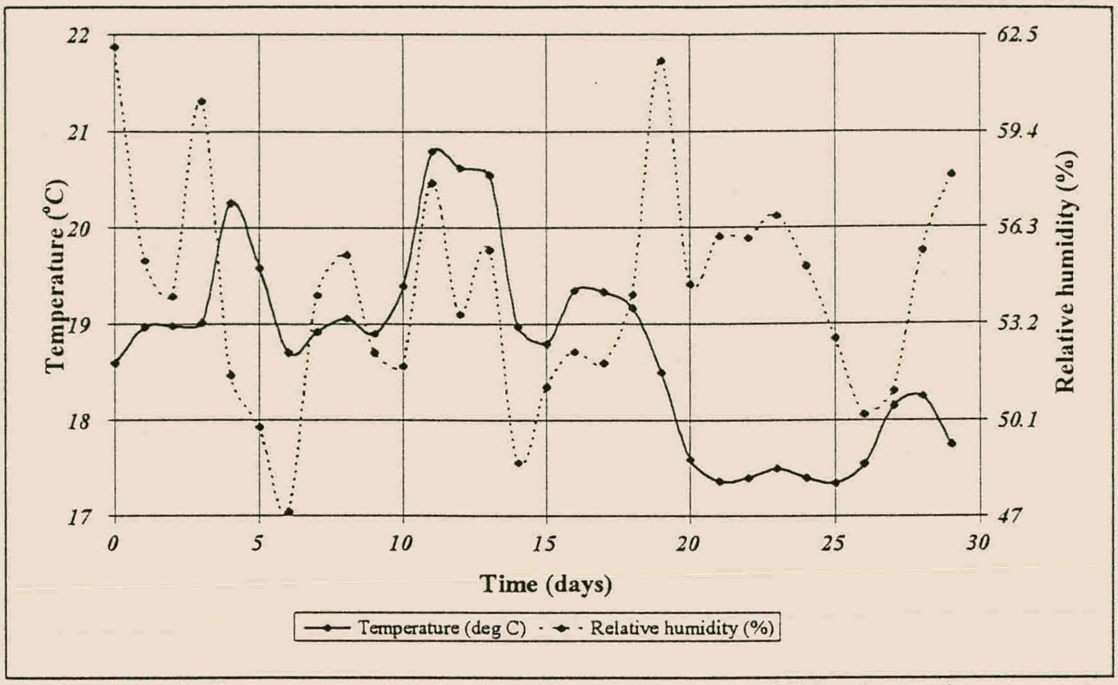


Figure 5-5: Daily average temperatures and relative humidities in environment 4

The average temperature was 18,8°C, with a standard deviation of 1,0°C and a coefficient of variation of 5,44%. The average relative humidity was 54,0%, with a standard deviation of 3,3% and a coefficient of variation of 6,05%.

5.6. Environment 5 - 20°C, 65% relative humidity

This drying regime aimed at an average of 20°C and a relative humidity of 65%. The simulation was conducted in a room in which temperature and relative humidity could be controlled. During the first week this drying regime overlapped with the fourth environment (20°C and 50% relative humidity) and saturated solutions of NH_4NO_3 were used to keep the humidity at 65%. At this stage the problem with the relative humidity control unit had been fixed and after a week (when the samples from environment 4 had been removed) the room's relative humidity was set to 65%.

Because there were no cyclic changes in either temperature or humidity, the conditions inside the room were noted on a regular basis over the full drying period. The final average temperature and relative humidity were found by using equations 5-2 and 5-3, calculating the weighted averages over the entire drying period.

The average conditions throughout the drying period are illustrated in Figure 5-6, on a scale of 1°C = 2,15% RH. The temperature fluctuated within a range of approximately 2,5°C, while the relative humidity fluctuations were in the order of an equivalent of approximately 4,5°C.

The average temperature was 18,0°C, with a standard deviation of 0,7°C and a coefficient of variation of 3,79%. The average relative humidity was 66,0%, with a standard deviation of 2,1% and a coefficient of variation of 3,25%.

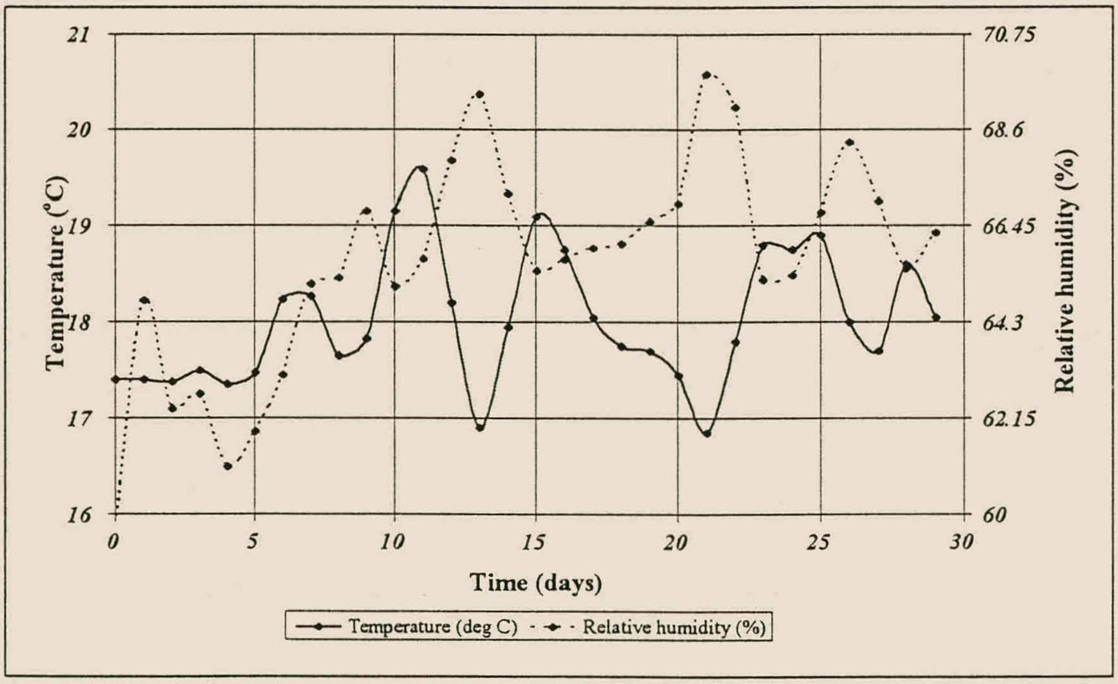


Figure 5-6: Daily average temperatures and relative humidities in environment 5

5.7. Environment 6 - 20°C, 80% relative humidity

This drying regime aimed at an average of 20°C and a relative humidity of 80%, using saturated solutions of NaCl. The simulation was conducted in an airtight cabinet inside a temperature controlled room. The average relative humidity in the room was 50%.

The cabinet had to be opened once a day for more than two weeks after casting, to add and weigh samples. It was found that the relative humidity inside the cabinet rose again swiftly from 50% to 80% after closing it and recovered within 30 to 45 minutes. During the initial stages, when new saturated samples were added on a frequent basis, the relative humidity tended to rise too high and reached levels of up to 95%. It was necessary to keep a constant watch on this problem and small quantities of dry $CaCl_2$ were used to bring the humidity down.

Because there were no cyclic changes in either temperature or humidity, the conditions inside the cabinet were noted on a regular basis over the full drying period. The final average temperature and relative humidity were found by using equations 5-2 and 5-3 and calculating the weighted averages over the entire drying period.

The average conditions throughout the drying period are illustrated in Figure 5-7, on a scale of 1°C = 1,2% RH. The fluctuations in relative humidity were significantly larger than the fluctuations in temperature, and in the order of an equivalent of approximately 10°C. This could significantly have influenced results obtained from this environment. The temperature fluctuated over a range of approximately 3,5°C.

There was one stage during the drying period when the temperature control unit failed, leading to rises in the room temperature. However, temperatures never exceeded 21,5°C before the problem was rectified. This failure happened after more than 2 weeks into the investigation, and should not have influenced the results obtained from this environment.

The average temperature was 19,1°C, with a standard deviation of 0,9°C and a coefficient of variation of 4,59%. The average relative humidity was 82,0%, with a standard deviation of 3,2% and a coefficient of variation of 3,87%.

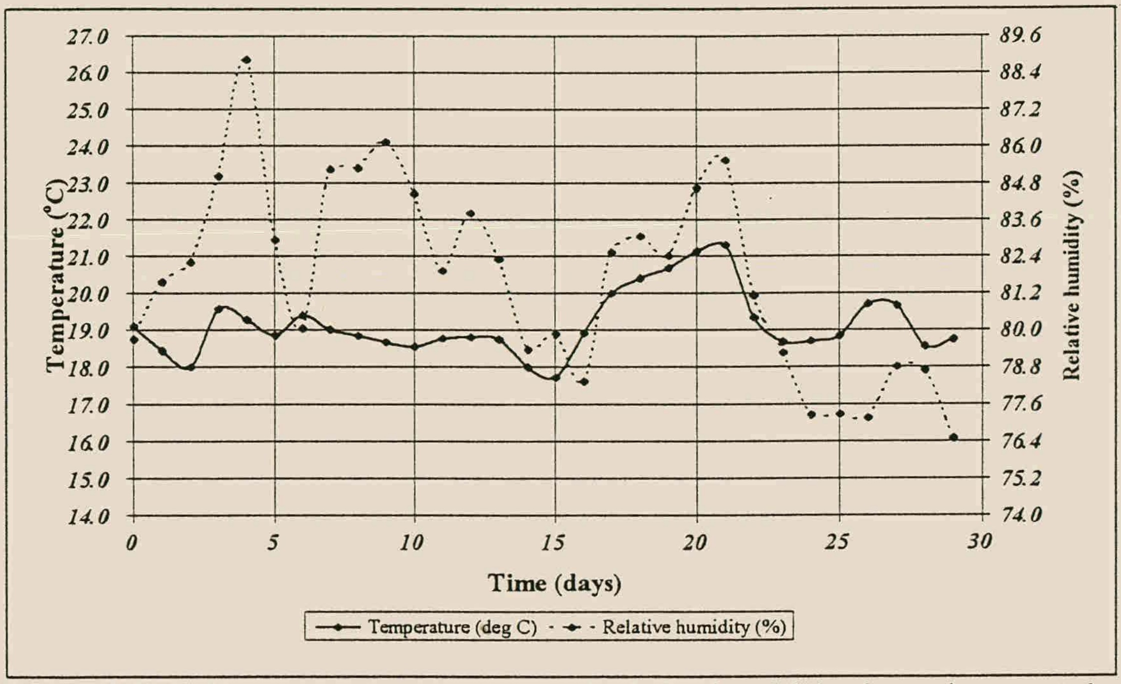


Figure 5-7: Daily average temperatures and relative humidities in environment 6

5.8. Wind speed assessment (environment 7)

The extent to which wind speed would influence the drying of hardened concrete and subsequent potential durability, was roughly assessed before undertaking any intensive and complex experimental procedures. The procedure followed is explained in section 4.6.1, and involved the drying of two sets of samples of the same grade and period of wet curing, under the same conditions (in terms of temperature and relative humidity). One set was left underneath a fan and the other in still air.

Temperature and relative humidity fluctuations were not important as far as magnitude were concerned, but only in the fact that they should stay the same for both the samples under controlled wind speed conditions and the samples in still air. The variation of these parameters are given in Appendix C.

Two experiments were conducted. The first experiment was an examination of 20 MPa concrete samples, wet cured for 1 day and the second 40 MPa concrete samples, wet cured for 7 days.

The samples under controlled wind speed were arranged in such a way that the wind speed over their surfaces was roughly the same. This was done by trial-and-error, using a wind anemometer approximately 10 mm above the centre of the surfaces of the samples in each configuration. The final arrangement was a ladder formation in front of the fan, with the highest 'step' closest to the fan.

The measured wind velocities over the surfaces of the samples were 6,26, 5,81, 5,36 and 4,92 m/s, starting at the highest 'step' closest to the fan and decreasing down the ladder. The average of these velocities was 5,58 m/s. This set-up was continued for a drying period of 22 days, before the samples were cored and subjected to the durability index tests.

5.9. Severity of drying conditions

In Chapter 2 (section 2.3.3.2.1) the severity of drying conditions was defined as the rate of evaporation, in $kg/m^2/hr$, which combined the effects of temperature and relative humidity. Thus the environmental conditions of drying regimes 2 to 6 can be compared and rated in terms of their overall severity towards early age drying of the concretes investigated (Figure 5-8). The range of simulated environmental conditions varied with almost one order of magnitude (Figure 5-9), giving a fairly comprehensive scope of possible drying conditions.

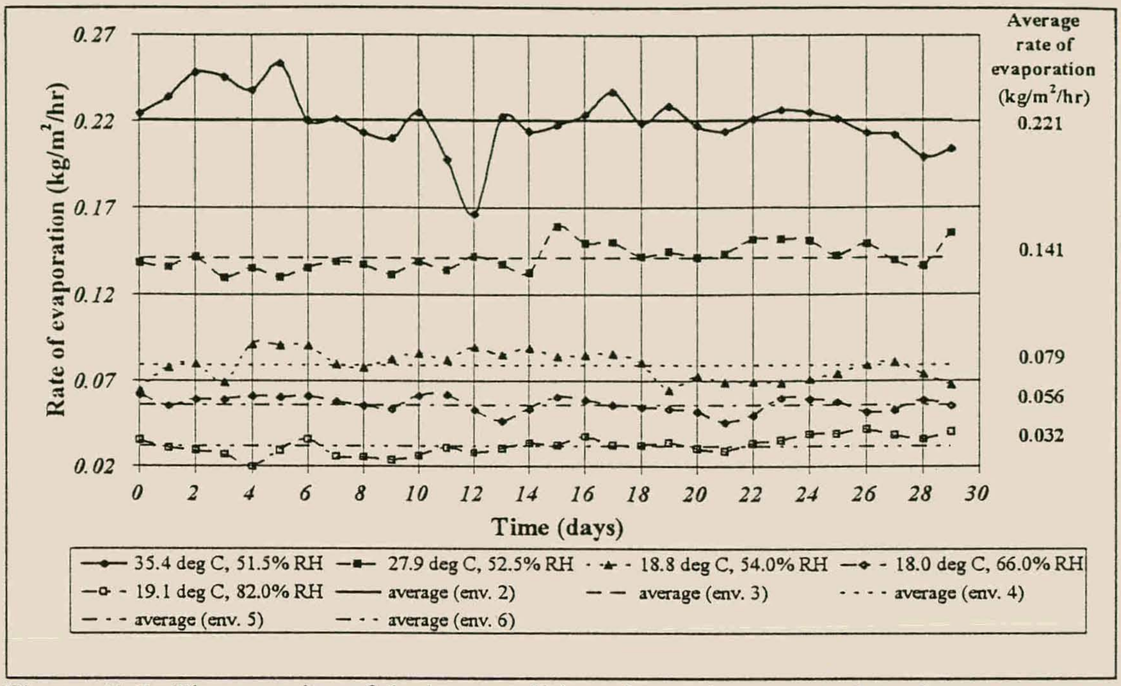


Figure 5-8: The severity of drying conditions in environments 2 to 6

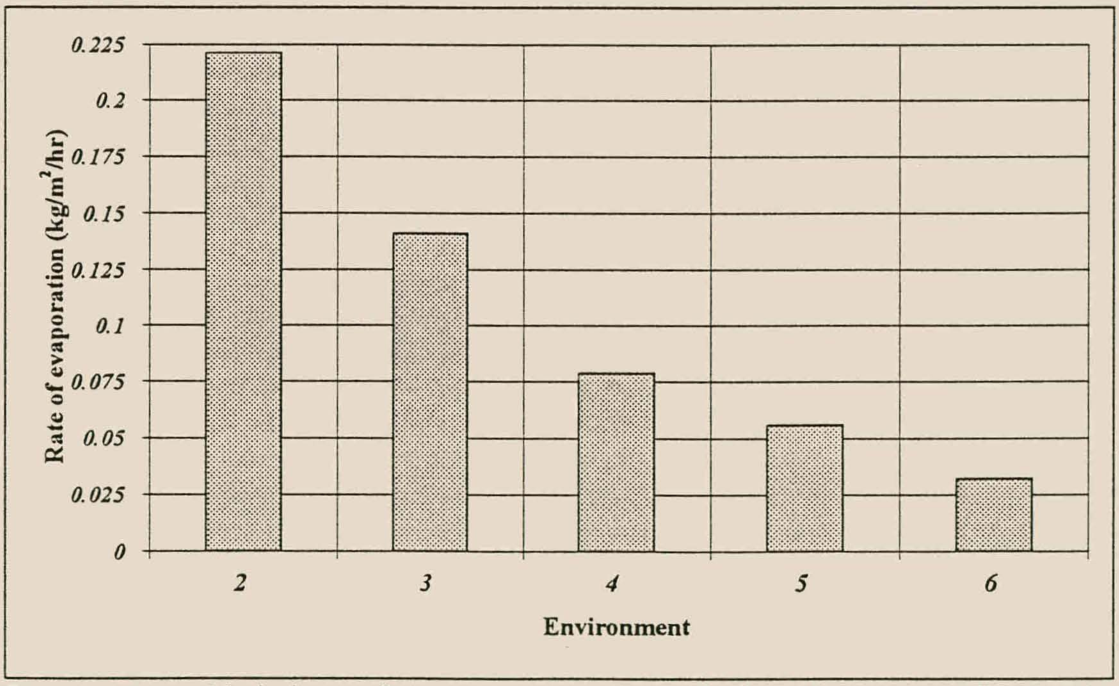


Figure 5-9: Variation of average severity of the drying conditions in environments 2 to 6

5.10. Conclusions

Different environmental conditions were successfully simulated in 7 different drying regimes. The average conditions are summarised in Table 5-2.

Table 5-2: Summary of environmental conditions in the drying regimes

Drying regime	Average temperature (°C)	Average relative humidity (%)	Average wind speed (m/s)
1	20,0 ± 2	100	0
2	35,3	51,5	0
3	27,9	52,5	0
4	18,8	54,0	0
5	18,0	66,0	0
6	19,1	82,0	0
7 :- 20 MPa :- 40 MPa	20,7 18,6	59,5 57,0	5,6 5,6

Fluctuations in temperature occurred and the absolute differences between measured minima and maxima throughout any specific drying period were typically in the order of 3 to 4°C. However, the peaks during which such extreme temperatures occurred were generally short-lived and the standard deviation from the average temperatures in the drying regimes were all less than 1°C.

The control of relative humidity proved to be more difficult and the absolute differences between measured minima and maxima were in some cases as much as 35% (or an equivalent of approximately 10°C). Fortunately the periods during which such extreme relative humidities occurred were brief (typically not more than half an hour to an hour in duration) and the standard deviations from the average measured relative humidities were typically in the order of 5%. However, this might still lead to some error in the interpretation of results and the detection of the trends in the investigation of the influence of relative humidity on the potential durability of concrete.

The peaks in relative humidity were mostly a result of adding wet samples to the confined spaces of the environmental chambers. This could be avoided by controlling the relative humidity of a larger space, which was not available at the time of this investigation.

During the evaluation of the influence of wind speed a domestic fan was used and constant wind velocities were generated for the duration of the drying periods.

In general the environmental stability of the drying regimes was adequate enough to be able to detect the general trends of the influence of the different environmental conditions on concrete drying and durability.

The severity of the drying conditions varied with almost one order of magnitude, giving a fairly comprehensive scope of possible drying conditions.

Table 5-3: Average severity of drying conditions in environments 2 to 6

Environment	Rate of evaporation ($kg/m^2/hr$)
2	0,221
3	0,141
4	0,079
5	0,056
6	0,032

6. MOISTURE LOSSES UNDER THE DIFFERENT ENVIRONMENTAL CONDITIONS

Since the ability of concrete to retain its moisture is directly related to its pore size distribution (the larger the pores, the more moisture is lost to evaporation) [Parrott, 1991], the amount of moisture lost is an indication of the quality of the covercrete in terms of porosity and diffusivity.

In this chapter the influences of w:c ratio, period of wet curing, temperature, relative humidity and wind speed on moisture losses from the concrete samples are presented. The influence of w:c ratio and wet curing will be discussed first. Moisture losses from some of the environments were not consistent. Environmental instabilities (discussed in the previous chapter) led to some anomalous results, but trends reflected in these anomalies were hidden by the general variability of the material. Therefore detailed comparisons between environmental fluctuations and deviations from general trends could not be made. The moisture losses from all the drying regimes are given in Appendix D.

The second part of the chapter deals with the influences of temperature and relative humidity on the drying of the different concrete grades. Finally the moisture losses measured from the two wind speed investigations are discussed.

6.1. The influence of w:c ratio and period of wet curing on moisture loss

For each environment, concrete grade and period of wet curing, five aluminium trays were cast, from which ten test cores could be retrieved. Each of these sets of trays were weighed on a daily basis for a week after start of exposure, and a final measurement was taken at the end of the drying period. The mass loss for each set was taken as the average of the moisture losses of the five trays, as a percentage of their original saturated masses.

6.1.1. General trends (environment 2 - 35,3°C and 51,5% RH)

As far as the influences of wet curing and w:c ratio are concerned, it was not possible to obtain more than general trends. As an example, the moisture losses from environment 2 (35,3°C, 51,5% RH) are given in Figure 6-1.

The period of wet curing seemed to play an important role in the ability of OPC concretes to retain its moisture during drying. There were marked improvements when the period of wet curing was increased from 1 to 3 days, while the difference between 3 and 7 days of wet curing did not lead to much more improvement. This seemed to be more important in the case of the lower grade concretes.

In Figure 6-2 the effects of w:c ratio and period of wet curing are better illustrated by plotting moisture losses after 7 days of drying against w:c ratio, for concretes wet cured for 1, 3 and 7 days (environment 2). The sensitivity of concretes of poorer quality to wet curing, under these conditions, is reflected in the difference in slopes of the lines for concretes wet cured for 1 and 3 days. It should be noted that this trend was only reflected in this particular drying regime. In the other (milder) drying regimes, all three concrete grades seemed to be equally sensitive to wet curing, as can be seen in a similar plot (Figure 6-3) from moisture losses in environment 4 (18,8°C, 54,0% RH).

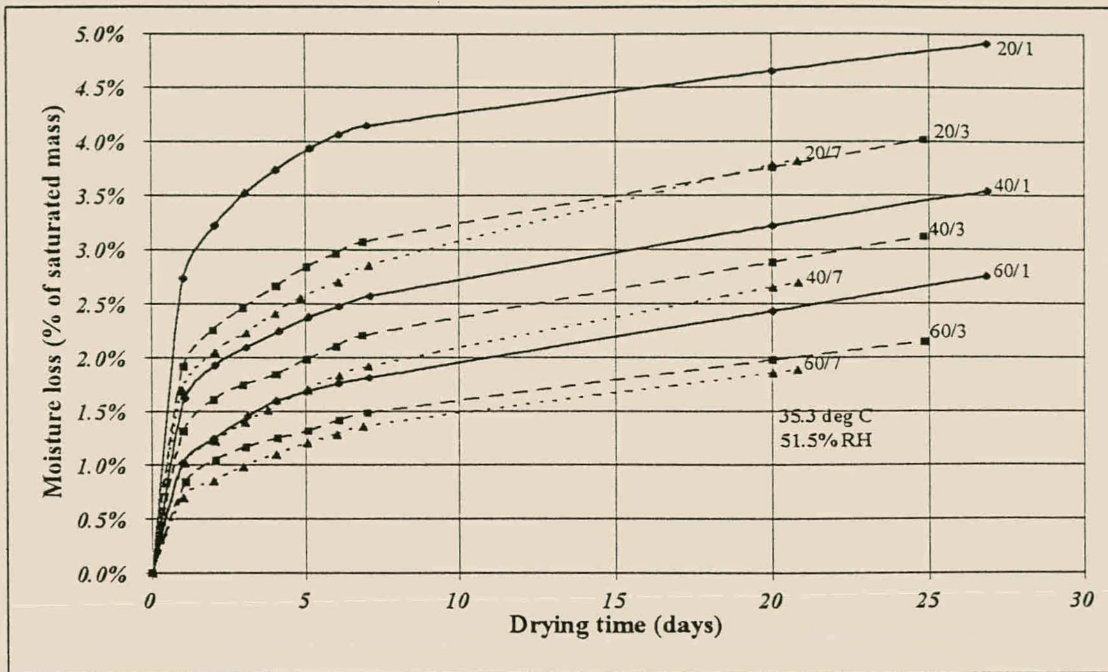


Figure 6-1: Moisture losses in environment 2*

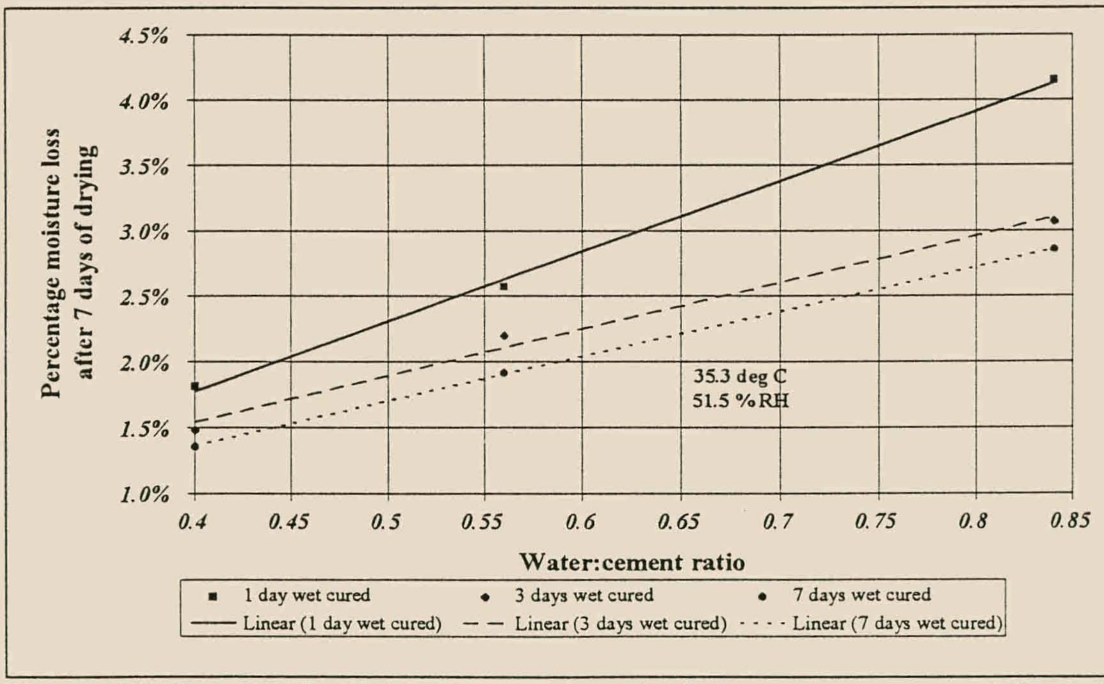


Figure 6-2: 7 day moisture loss versus w:c ratio for concretes wet cured for 1, 3 and 7 days (environment 2)

* Note that the lines are identified with respect to the concrete grade and the period of wet curing. For example 20/7 means the average moisture losses from five concrete samples of grade 20 MPa that have been wet cured for 7 days.

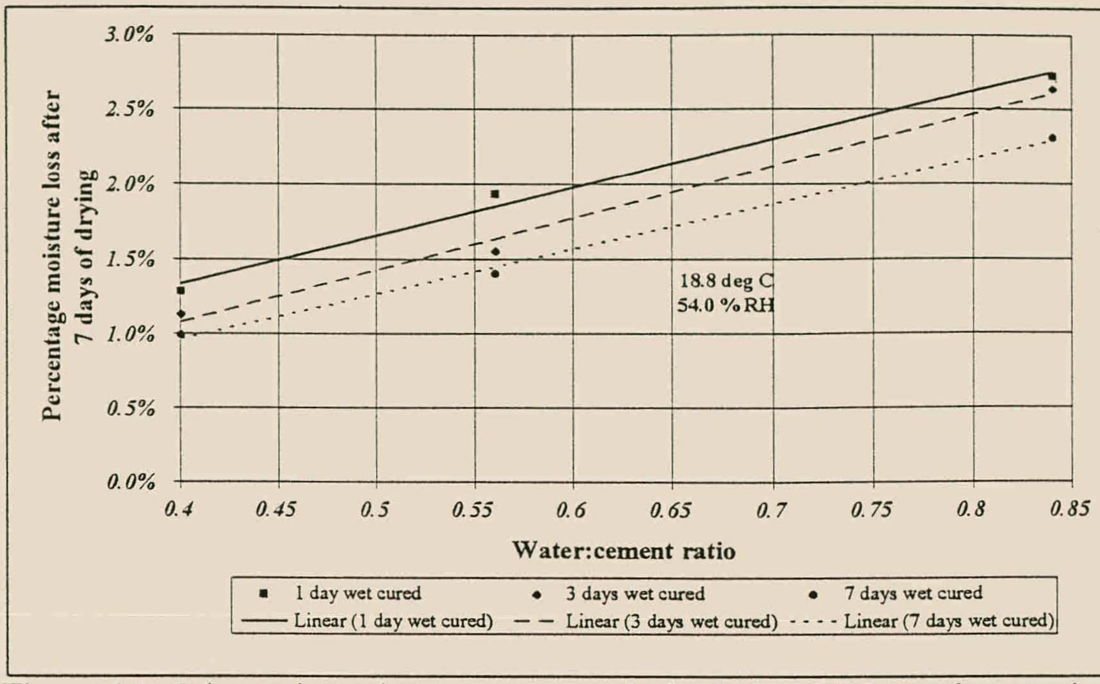


Figure 6-3: 7 day moisture loss versus w:c ratio for 1, 3 and 7 days of wet curing (environment 4)

6.1.2. Moisture losses in the other drying regimes

The trends observed in environment 2 were not necessarily true for all the drying regimes. In some cases, concretes wet cured for longer periods of time lost more moisture than poorer cured concretes of the same grade. In other cases, the difference between 1 and 3 days of wet curing was less marked than between 3 and 7 days. Possibly an important reason for these anomalies was some unstable environmental conditions during early stages of drying (typically during the first 3 days of exposure of a particular set of samples.

The variability of the material also played a role, especially since the direction of drying was parallel to the direction of casting. Thus results were likely to be affected by factors such as bleeding channels, and the sensitivity of the material to fluctuations in temperature and relative humidity was “masked” by non-homogenous material properties.

Some typical anomalous results were observed in environment 3 (17,9°C and 52,5% RH), where the 60 MPa samples, wet cured for 1 day, lost less moisture than those wet cured for 3 days (Figure 6-4). Moisture losses from 40 MPa samples, wet cured for 1 and 3 days, were almost the same, with a larger difference between 3 and 7 days of wet curing.

The environmental conditions during the first 13 days are illustrated in Figure 6-5. In this figure, the headings at the top of the plot indicate when the particular set of samples was removed from the curing tank and placed inside the drying regime (exposure time = 0 days). The values for temperature and relative humidity are calculated averages for the particular day, and given on a scale of 1°C = 2,95% RH (see Table 5-1). For clarity, the environmental simulation is shown from the start, and the addition of all sample sets are included.

From Figure 6-5 it can be seen that fluctuations of temperature and relative humidity were relatively small, i.e. within approximately 1,4°C and 6,5% RH (or an equivalent of approximately 2°C) respectively. Thus the differences in environmental conditions, for the 60/1 and 60/3 samples, during the initial stages of drying, were minor, and cannot be effectively used to explain the anomalous mass loss data of these two sets of samples. The moisture losses observed in the rest of the drying regimes are given in Appendix D.

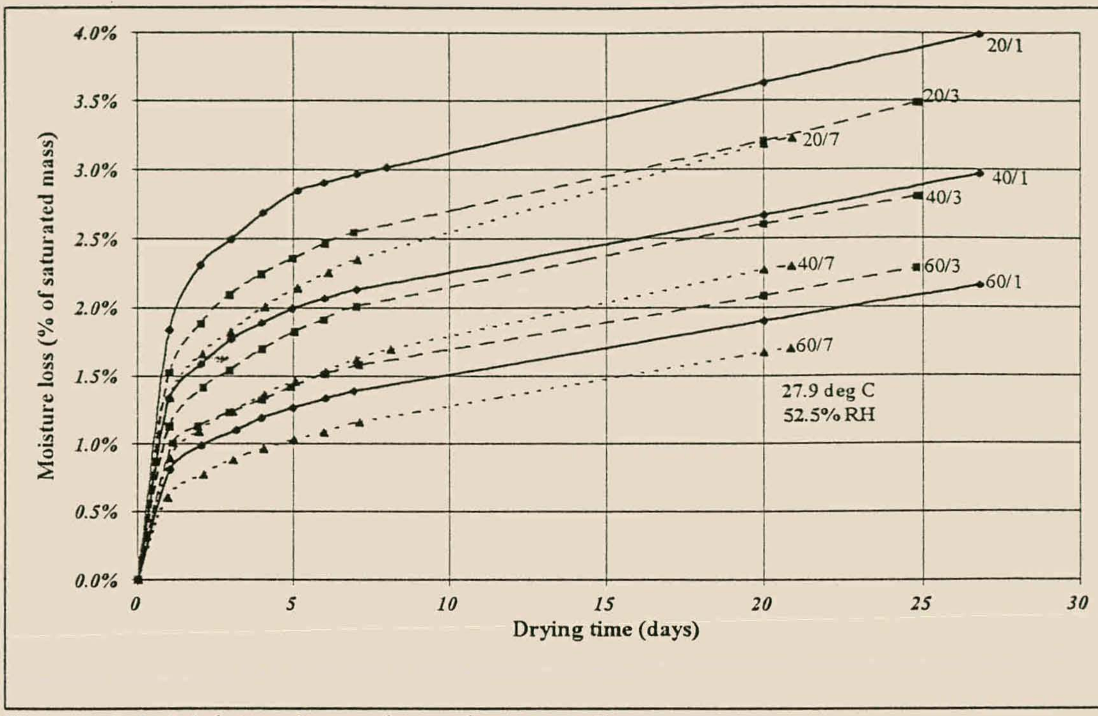


Figure 6-4: Moisture losses in environment 3

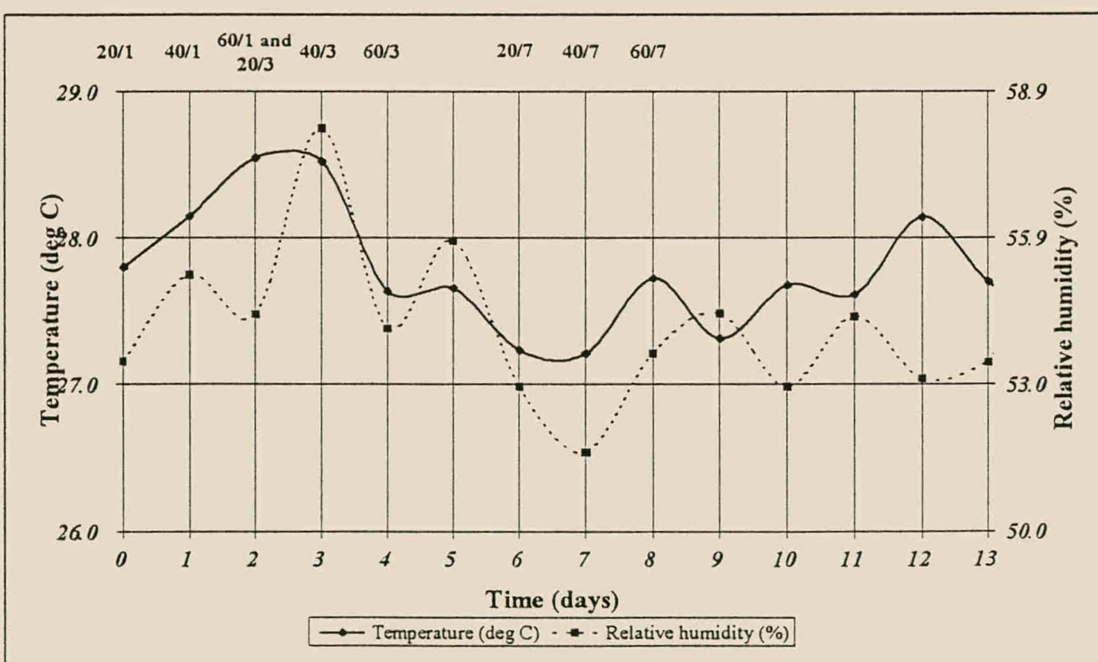


Figure 6-5: Temperature and relative humidity during the first 13 days in environment 3

6.1.3. Moisture loss in environment 6

The drying of concrete under very humid conditions (above 80% RH) seemed to be sensitive to fluctuations in relative humidity, especially during the first 5 days. This can be illustrated by plotting the mass loss data of environment 6 (19,1°C and 82,0% RH) for this period of time (Figure 6-6).

During the first few days of this environmental simulation, problems were encountered with relative humidity control, causing larger fluctuations than planned. Within this relative humidity range, the relationship of the radius of menisci to this parameter is highly non-linear. The result on concrete drying is evident in Figure 6-6, apparent in the change in slopes of some of the mass loss curves.

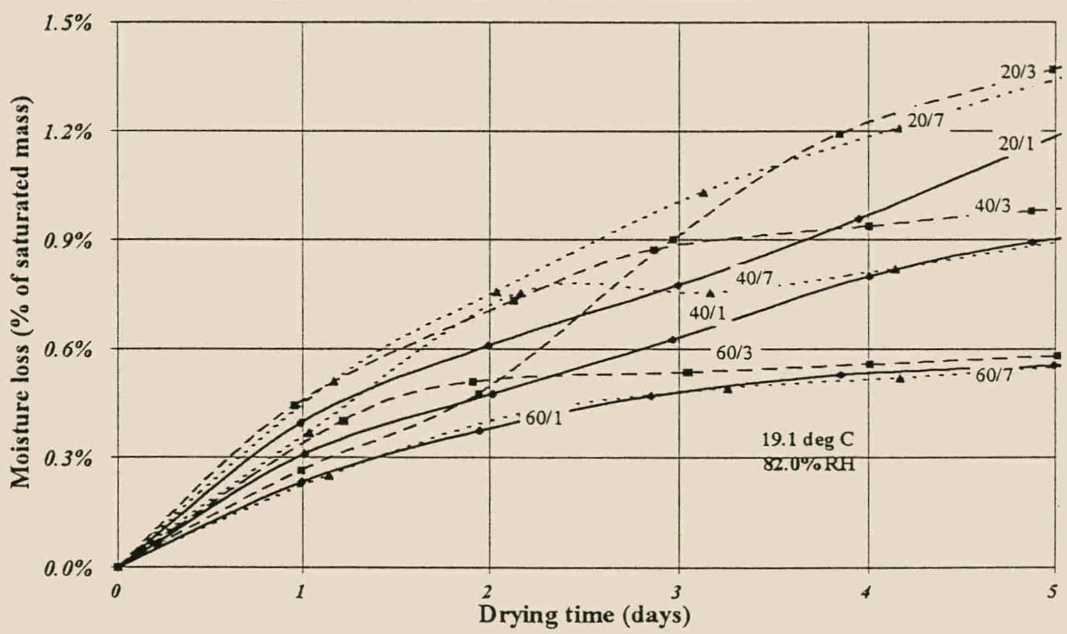


Figure 6-6: Moisture losses in environment 6 during the first 5 days of drying

6.2. The influence of temperature on moisture loss

The exact influence of temperature on the moisture loss of concrete samples was difficult to assess. The three environments used for the investigation of the influence of temperature were drying regimes 2, 3 and 4, with average temperatures of 35,3, 27,9 and 18,8 °C respectively. The corresponding average relative humidities in these environments were 51,5, 52,5 and 54,0%.

Three types of behaviour occurred:

1. A large difference between moisture losses in environments 2 and 3, with a small difference between moisture losses in environments 3 and 4. An example of this is illustrated in Figure 6-7, for concretes of 20 MPa, wet cured for 3 days. This kind of behaviour was observed for all the 20 MPa concretes, irrespective of the curing time involved.
2. A larger difference in moisture losses in environments 3 and 4, than in environments 2 and 3 (Figure 6-8). This did not occur in many cases, and the differences were not as pronounced as in the case of the 20 MPa concretes. The only case where this poses a problem in the subsequent discussion, is in the case of 60 MPa concretes, wet cured for 3 days. In this case there was slightly more moisture lost from concretes drying at 27,9°C than at 35,3°C. This is illustrated in Figure 6-9, and was most likely a result of material variability.
3. Similar differences in moisture losses in environments 2 and 3, as in environments 3 and 4 (Figure 6-10). This seemed to be the general trend for the 40 and 60 MPa concretes.

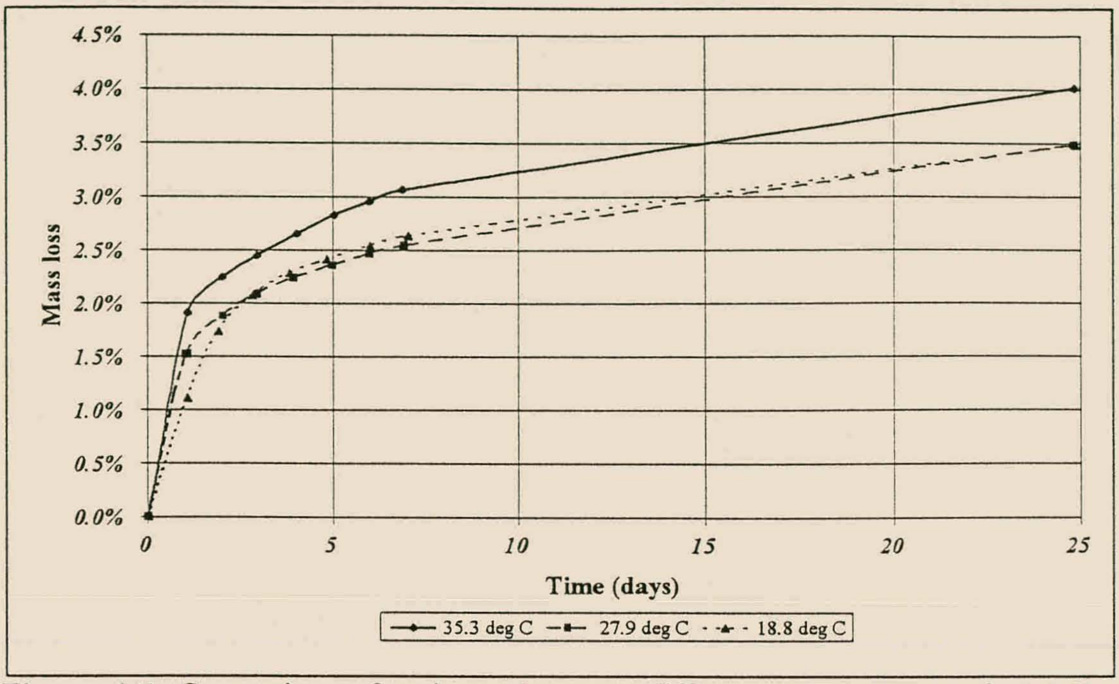


Figure 6-7: Comparison of moisture losses at different temperatures of 20 MPa concretes, wet cured for 3 days

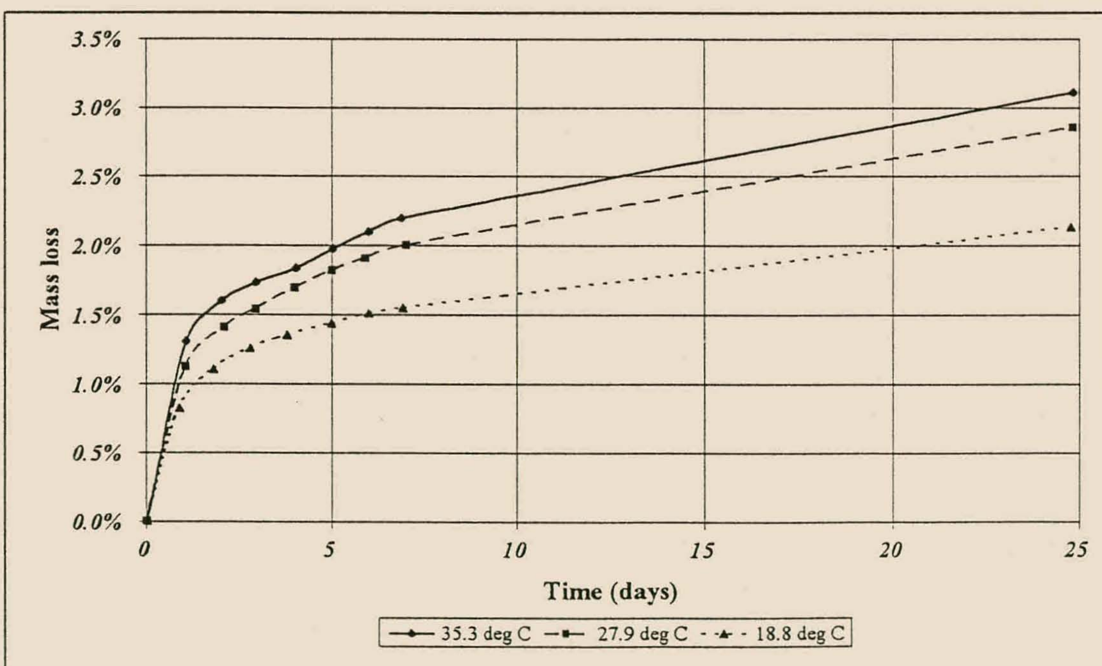


Figure 6-8: Comparison of moisture losses at different temperatures of 40 MPa concretes, wet cured for 3 days

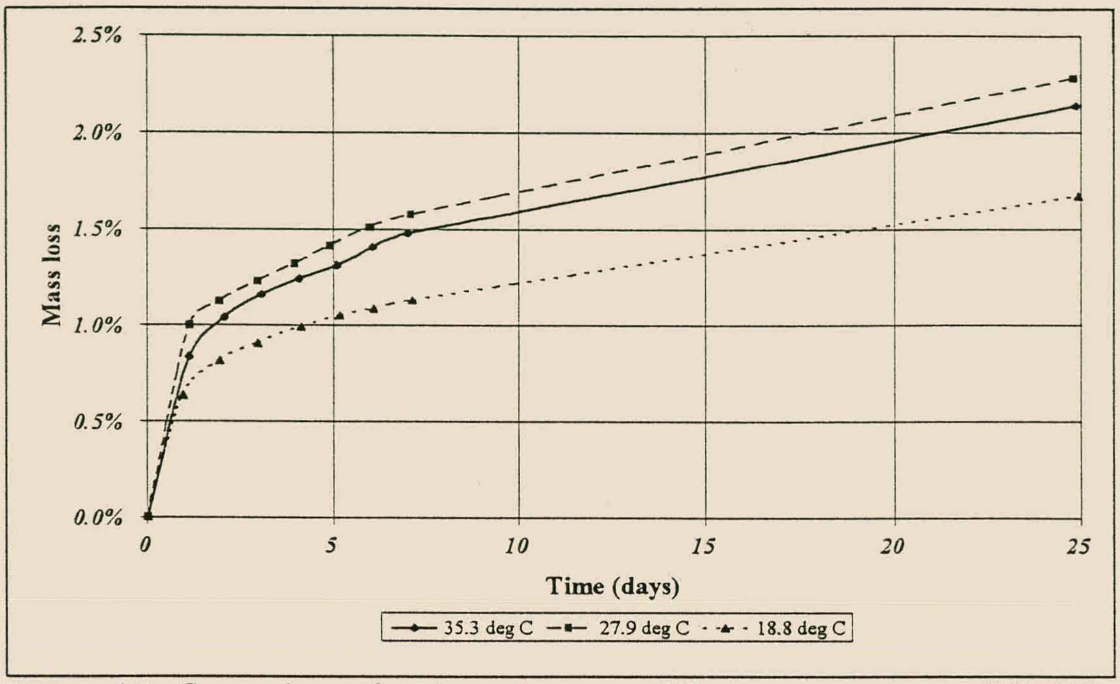


Figure 6-9: Comparison of moisture losses at different temperatures of 60 MPa concretes, wet cured for 3 days

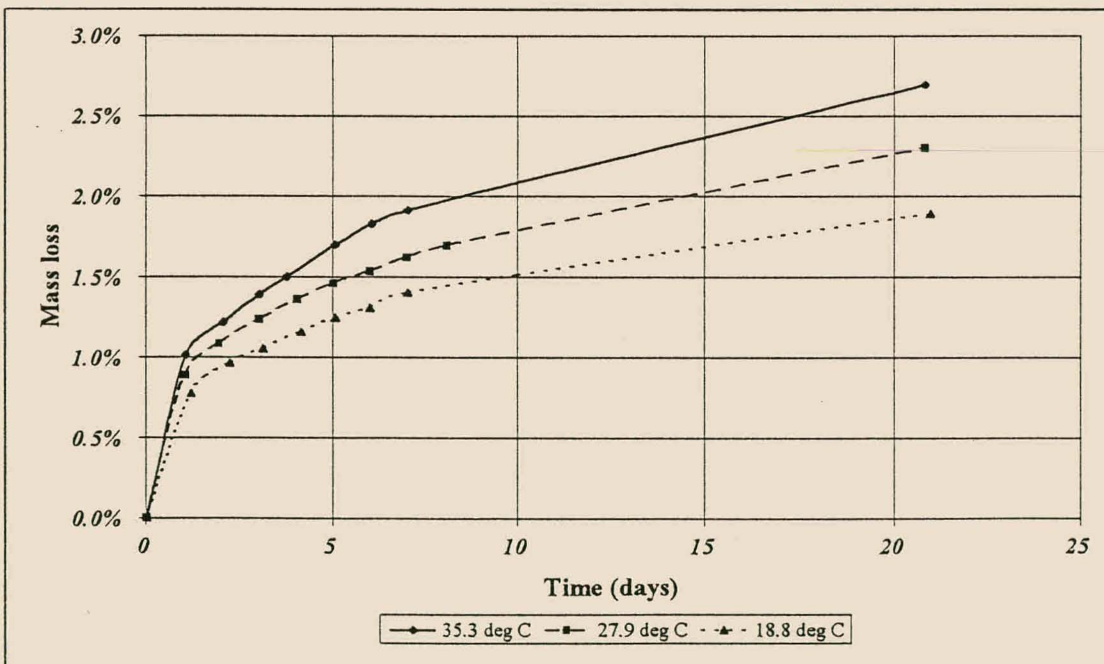


Figure 6-10: Comparison of moisture losses at different temperatures of 40 MPa concretes, wet cured for 7 days

6.2.1. 40 MPa and 60 MPa concretes

The relationship between moisture loss and temperature, for 40 and 60 MPa concretes, is illustrated in Figure 6-11. Note that the line for 60 MPa concretes, wet cured for 3 days (see point 2. in 6.3), was omitted from this curve, in order to illustrate the apparent trend of the influence of temperature on moisture loss from reasonable (40/1) to good (60/7) quality concretes.

A few comments on this figure are:

- Linear trend lines provided the best fit for the data, with R^2 values ranging from 0,97 to 1,00. The amount of moisture lost decreased with increasing grade and curing time.
- The slopes of the lines flattened with increasing curing time, indicating the sensitivity to the effects of temperature. This seems to be similar for these two concretes, by comparing the slopes of 40/1 and 60/1, as well as 40/7 and 60/7.

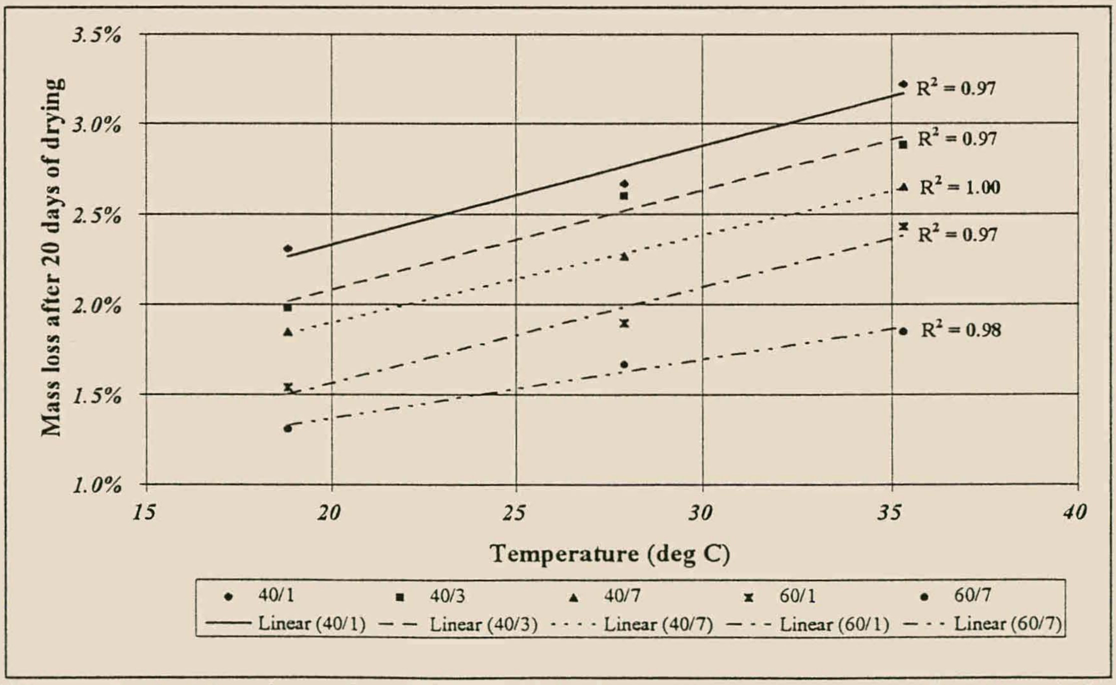


Figure 6-11: Mass loss after 20 days of drying versus temperature, for 40 and 60 MPa concretes

6.2.2. 20 MPa concretes

The 20 MPa concrete seemed to behave differently than the higher grades. The non-linear relationship between moisture losses from this grade and temperature is illustrated in Figure 6-12. No consistent trend lines could be fitted for this data.

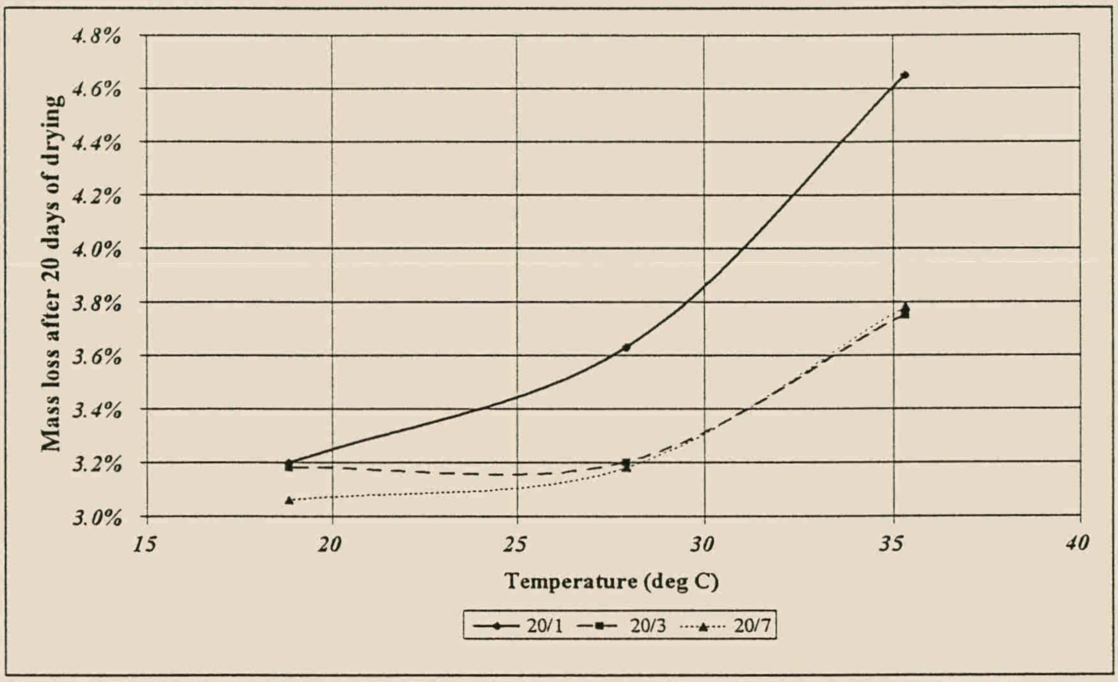


Figure 6-12: Mass loss after 20 days of drying versus temperature, for 20 MPa concretes

6.3. The influence of relative humidity on moisture loss

The three environments used for the investigation of the influence of relative humidity were drying regimes 4, 5 and 6, with average relative humidities 54,0, 66,0 and 82,0% respectively. The corresponding average temperatures in these environments were 18,8, 18,0 and 19,1°C respectively.

- The influence of relative humidity on the ability of OPC concretes to retain their moisture ranged from highly non-linear to almost linear. In the case of poorly cured concretes of all the grades under investigation, there were large differences between moisture losses at 82,0% and 66,0% RH, with much less marked differences between 66,0% and 54,0% RH (Figure 6-13). As the period of wet curing increased, the relationship between moisture loss and relative humidity became more linear, as can be seen in Figure 6-14.

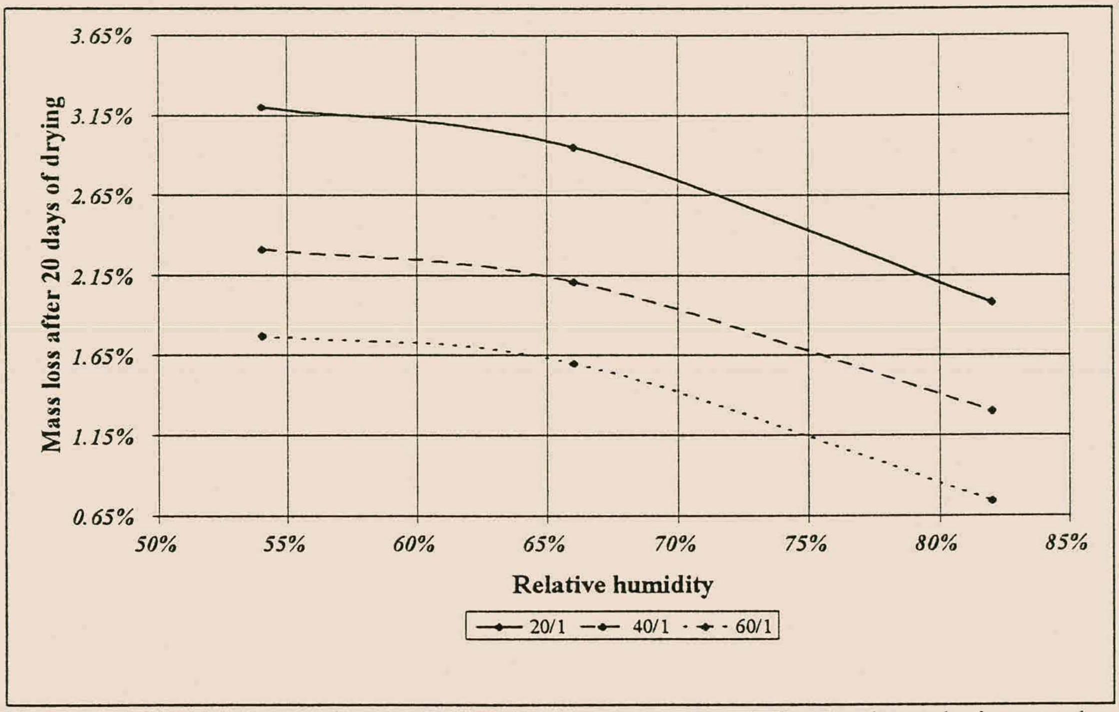


Figure 6-13: Moisture losses of concretes wet cured for 1 day, drying under different relative humidities

Plotting Figures 6-13 and 6-14 on the same graph (Figure 6-15), the following observations can be made:

- Less moisture was lost from concretes with lower w:c ratios.
- Less moisture was lost from concretes of the same w:c ratio, but wet cured for longer periods of time. This seemed to have a greater effect for the 40 and 60 MPa than for the 20 MPa concretes.
- The effect of wet curing becomes insignificant at relative humidities higher than 80%, for all concrete grades.

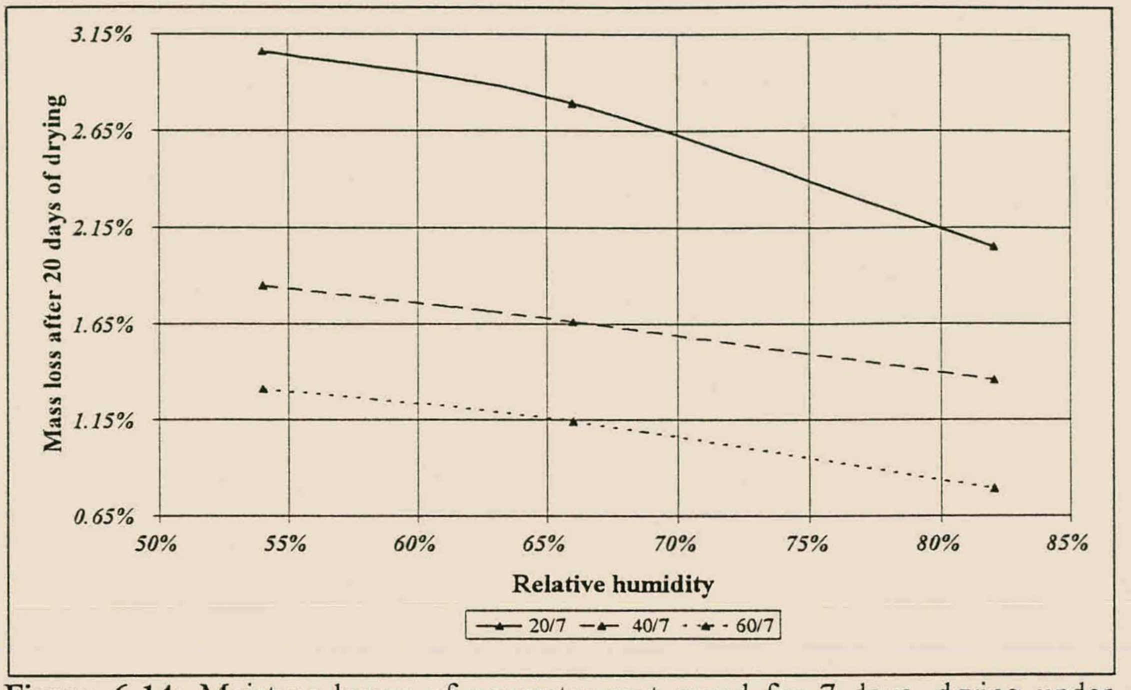


Figure 6-14: Moisture losses of concretes wet cured for 7 days, drying under different relative humidities

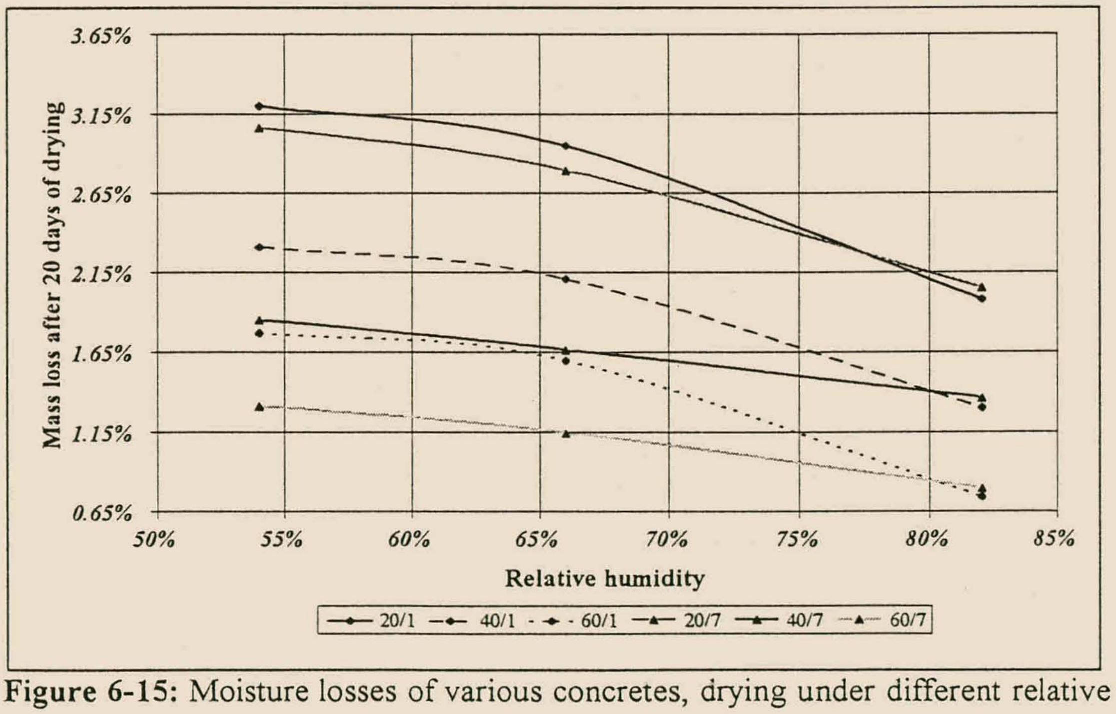


Figure 6-15: Moisture losses of various concretes, drying under different relative humidities

6.4. The influence of wind speed on moisture loss

Two preliminary investigations were done on the importance of the influence of wind speed on the drying of concrete and the resulting potential durability. The method statement is given in section 4.6.1. The effect of an applied wind speed on moisture losses is given in the following paragraphs.

6.4.1. Drying of 20 MPa concrete, wet cured for 1 day

An average wind speed of approximately 5,6 m/s was applied for a period of 23 days over four concrete samples of 20 MPa that had been wet cured for 1 day. Another four samples of the same batch were left in the same room (and thus the same environment in terms of temperature and relative humidity) in still air.

This specific concrete grade and period of wet curing were selected because it was felt that a poor quality concrete would be the most sensitive to any effect wind speed might have on drying processes and potential durability. The moisture losses of the samples were measured and the results are shown in Figure 6-16.

It can be seen that the samples under controlled wind speed lost slightly more moisture than the ones in still air. The difference was established within the first 48 hours of drying. After that the two curves stayed parallel and fluctuated concurrently during ambient temperature and relative humidity changes. The final average difference in moisture loss between the two sets of samples was 0,37%.

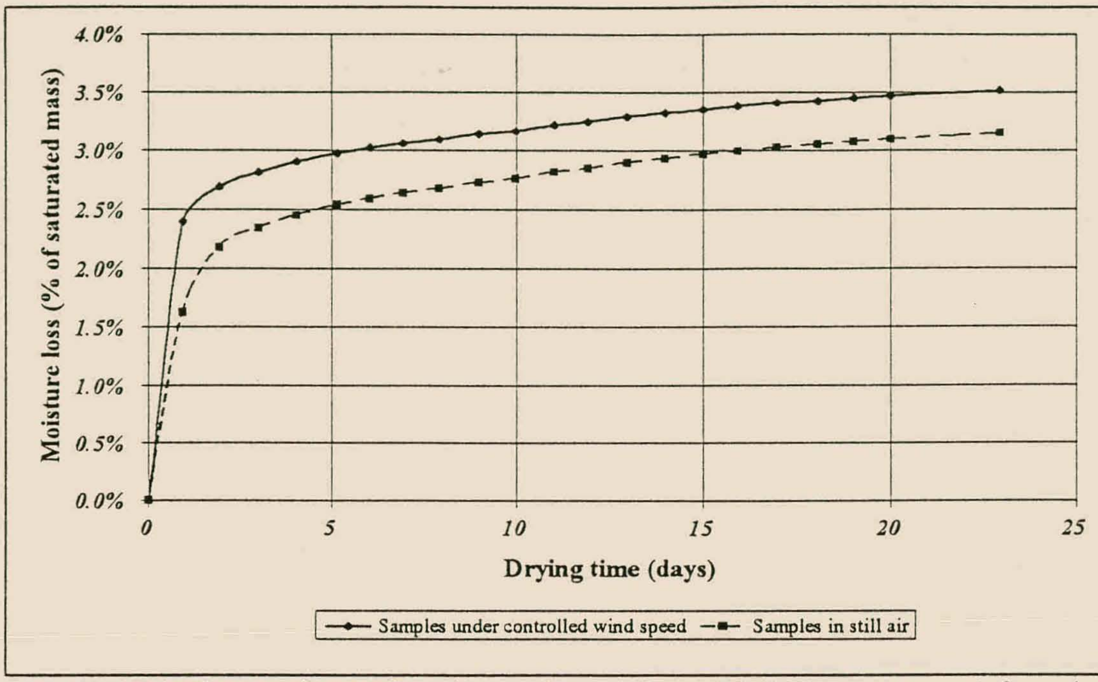


Figure 6-16: Comparison of moisture losses from 20 MPa concrete left under controlled wind speed and in still air

6.4.2. Drying of 40 MPa concrete, wet cured for 7 days

An average wind speed of approximately 5,6 m/s was applied for a period of 21 days over four concrete samples of 40 MPa that have been wet cured for 7 days. Another four samples of the same batch were left in the same room, in still air.

This specific concrete grade and period of wet curing were selected in contrast to the 20 MPa samples, representing a much better quality concrete. The moisture losses of the samples were measured and the results are shown in Figure 6-17.

It can be seen that the samples under controlled wind speed and the ones in still air lost almost exactly the same amount of moisture. The final average difference in moisture loss between the two sets of samples was 0,02%.

6.5.2. The influence of temperature

1. The effect of temperature on the drying of concrete increases with time. Moisture is initially lost mostly from the larger pores and increasingly from smaller capillaries as time progresses.
2. By considering moisture losses of concrete samples at different stages of its drying history, it is not possible to distinguish between changes in pore structure and the increasing influence of temperature on evaporation. A more direct measurement of pore structure is necessary, and is done in Chapter 7 with the use of the durability index tests.
3. Trends in moisture loss from lower grades differ from those from higher grades.

6.5.2.1. 40 and 60 MPa concretes

- The relationship between moisture loss and temperature for these concretes could be represented with linear trend lines. The amount of moisture lost decreased with increasing grade and curing time, indicating general concrete quality variations.
- The slopes of the lines flattened with increasing curing time, indicating the sensitivity to the effects of temperature, which were similar for these two concretes.

6.5.2.2. 20 MPa concretes

- The 20 MPa concrete showed a non-linear relationship for moisture loss versus temperature.

6.5.3. The influence of relative humidity

1. The influence of relative humidity on the ability of OPC concretes to retain their moisture ranged from highly non-linear to almost linear. In the case of poorly cured concretes of all the grades under investigation, there were large

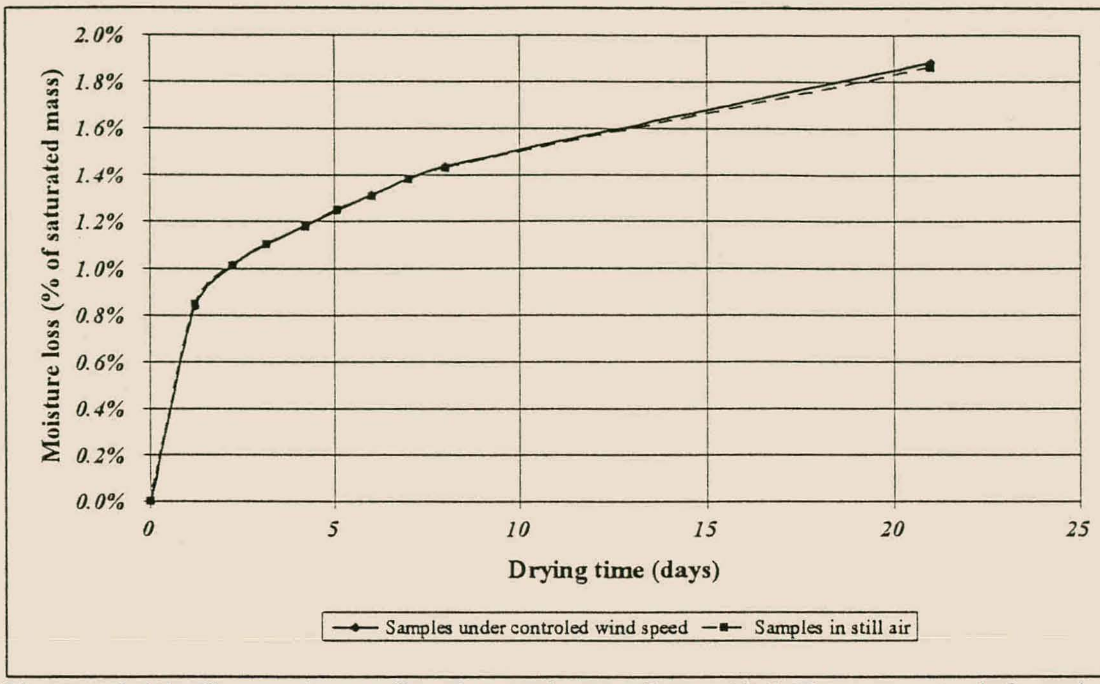


Figure 6-17: Comparison of moisture losses from 40 MPa concrete left under controlled wind speed and in still air

6.5. Conclusions

6.5.1. The influence of w:c ratio and period of wet curing

1. The relationship between w:c ratio and moisture loss could be represented with linear trend lines. Higher w:c ratios resulted in larger moisture losses.
2. The period of wet curing seemed to play an important role in the ability of OPC concrete to retain its moisture during drying. There were marked improvements when the period of wet curing was increased from 1 to 3 days, while the difference between 3 and 7 days of wet curing didn't lead to much more improvement. This was more significant in the case of concretes with higher w:c ratios.
3. Variations in these trends occurred as a result of material variability and some unstable environmental behaviour during early stages of drying.
4. Under very humid conditions (above 80% RH), the rate of moisture loss of concrete is generally very sensitive to changes in relative humidity.

differences between moisture losses at 82,0% and 66,0% RH, with much less marked differences between 66,0% and 54,0% RH. As the period of wet curing increased, the relationship between moisture loss and relative humidity became more linear.

2. The following trends were observed:
    - Less moisture was lost from concretes of the same w:c ratio, but wet cured for longer periods of time. This seemed to have a greater effect for the 40 and 60 MPa than for the 20 MPa concretes.
    - The effect of wet curing becomes insignificant at relative humidities higher than 80%, for all concrete grades.

6.5.4. The influence of wind speed

1. The influence of wind speed did not have a significant influence on the moisture loss of hardened concrete.
2. Even in the case of the 20/1 concrete, the final moisture losses of the samples drying in still air were almost 90% as much as the ones drying under controlled wind conditions. Since concrete of such poor quality is rarely used anymore in modern construction, the influence of wind on concrete drying (after setting) can be disregarded.

7. The Results of the Durability Index Tests

In this chapter the durability index test results are discussed. These include assessments of indexes of chloride conductivity, oxygen permeability and water sorptivity, for concretes of varying grades and periods of wet curing, drying under different environmental conditions. The primary objective is to determine and rate the importance of the influences of temperature, relative humidity and wind speed on the potential durability of the concretes investigated.

The influence of w:c ratio and period of wet curing can be illustrated using the fully wet cured results from environments 2 to 6. In general trends were clear, but occasionally some anomalous experimental scatter occurred. These could be due to the following:

- Generally cores used for the durability index tests are retrieved perpendicular to the direction of casting. This is done to minimise the influence of factors such as bleeding channels on results. During this investigation cores were retrieved parallel to the direction of casting, as a result of the method used to allow uniaxial drying. Thus the results could be expected to show a larger variability than those obtained in the normal way.
- The occasional environmental instabilities in some of the drying regimes (as discussed in Chapters 5), particularly in the first few days of exposure, could have caused some variations from the general trends.

Mathematical curve fitting could not applied consistently, due to the limited amount of data points. In order to illustrate the general trends, it was thus necessary in some cases to adjust the results obtained. The criteria used to do this were based on:

- The trends of other concretes in the same drying regime.
- The general trend of the particular concrete grade with respect to the appropriate index test.
- The relative performance of such concretes under varying temperatures and relative humidities.

In general the trends of the three concretes grades were similar. However, in some cases the 20 MPa concrete behaved somewhat differently than the better quality concretes. The trends of the 40 and 60 MPa concretes were very similar under all conditions. Therefore, the subsequent discussion will distinguish between low quality concretes (20 MPa) and medium to high quality concretes (40 and 60 MPa).

The second part of the chapter deals with the influences of temperature and relative humidity, as well as the trial investigations on the influence of wind speed and direction of casting.

7.1. The influence of w:c ratio and period of wet curing on the durability indexes

7.1.1. The influence of w:c ratio

For each of environments 2 to 6, extra samples were cast and fully wet cured (at 20°C) for a 28 day period and subjected to the durability index tests. Using these results, the average indexes for chloride conductivity, oxygen permeability and water sorptivity were calculated for each of the three concrete grades investigated (Table 7-1). These averages were used as references for comparing measured properties of the three concrete grades, wet cured for varying periods of time and drying under different environmental conditions.

Table 7-1: Fully cured results of the durability index tests

Concrete grade (MPa)	Chloride conductivity index (mS/cm) of the fully cured samples from environment: 2	3	4	5	6	Mean fully cured result	Coef-ficient of variation
20	2,71	2,59	2,47	2,62	2,45	**2,57**	**4,2%**
40	1,85	1,51	1,39	2,12	2,00	**1,77**	**17,7%**
60	1,38	0,84	0,96	1,32	1,35	**1,17**	**21,5%**
	Oxygen permeability index of the fully cured samples from environment: 2	**3**	**4**	**5**	**6**		
20	9,30	9,22	9,41	9,38	9,60	**9,38**	**1,5%**
40	10,09	9,95	10,05	10,06	10,21	**10,07**	**0,9%**
60	10,37	10,14	10,39	10,34	10,42	**10,33**	**1,1%**
	Water sorptivity index (mm/√h) of the fully cured samples from environment: 2	**3**	**4**	**5**	**6**		
20	11,78	10,66	10,10	10,95	10,25	**10,75**	**6,2%**
40	8,77	8,71	8,00	8,75	9,21	**8,69**	**5,0%**
60	7,95	8,59	7,97	8,67	9,21	**8,48**	**6,2%**

The variability mentioned in the introduction of this section, is evident in some of these average values (especially in the chloride conductivity results). Apart from factors like bleeding channels, variations can also be ascribed to slight differences in w:c ratio, water content and compaction. However, none of the average values were discarded, and the data in Table 7-1 will be used to normalise the results obtained from the different drying regimes. Furthermore, the average values in this table will be used in Chapter 9 when a theory of the drying of concrete is formulated, and should be representative of all the concrete batches.

The average values for the durability indexes can be used to compare the fully cured performance of the three concrete grades. Potential durability properties ranged from very poor to fairly good, and represented all the OPC concretes most commonly used in everyday construction.

7.1.2. The influence of wet curing (environment 4 - 18,8°C, 54,0% RH)

The results of the durability indexes obtained from this environment are illustrated in Figure 7-1. The average values of Table 7-1 are also indicated, to illustrate the relative performance of any concrete batch with respect to the separate batches of fully cured samples. Note that all 28 day results represent 20°C conditions. Also, the smoothing indicated in the legend are not applicable for all the data, but only for lines not plotted directly through the data points (e.g. the water sorptivity of the 60 MPa concretes). The experimental data of the different drying regimes (actual and smoothed results) is supplied in Appendix E.

7.1.2.1. Index results for the 20 MPa concrete

Wet curing for at least 3 days seemed to be necessary for these concretes. Extending the curing period to 7 days resulted in an oxygen permeability index similar to fully cured results. The water sorptivity and chloride conductivity indexes still improved markedly when the curing period was extended to 28 days. Note that the fully wet cured curing temperature (20°) and that of this environment (18,8°C) were similar.

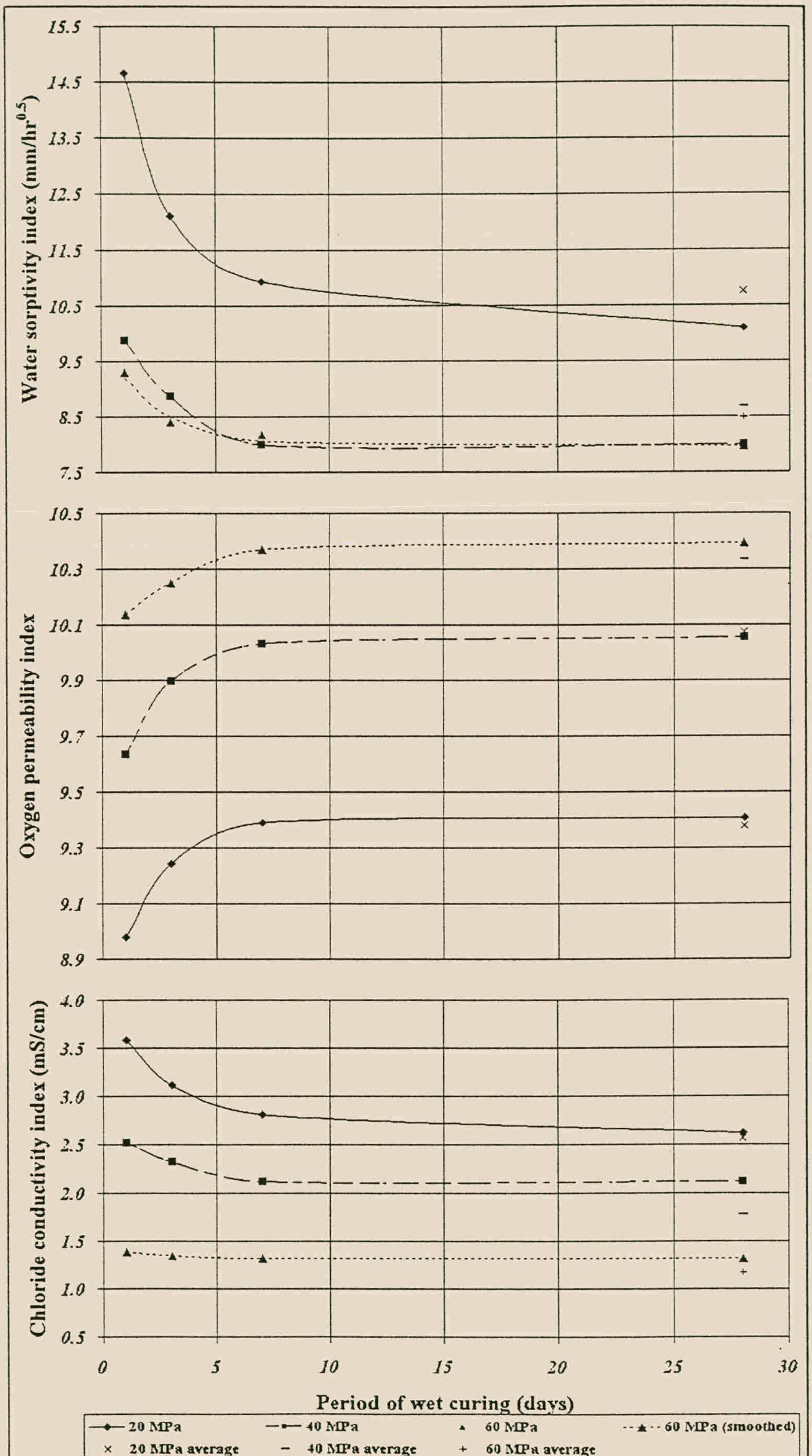


Figure 7-1: Durability indexes obtained from environment 4 (18,8°C, 54,0% RH)

7.1.2.2. Index results for the 40 and 60 MPa concretes

Wet curing was not as critical for these higher grade concretes, especially for the chloride conductivity index. Three days of wet curing were adequate for performance in terms of the other two indexes. Wet curing for 7 days resulted in similar indexes obtained from the fully cured concretes.

7.2. The influence of temperature on the durability index results

Variations in temperature had an important impact on the potential durability of all the concretes investigated. Depending on the concrete grade and period of wet curing, elevated temperatures could either badly impair, or significantly improve the development of durability properties. This was the result of the combined effect of temperature on the rates of evaporation and cement hydration.

Due to the slight variations in quality of concretes of the same grade, but from different drying regimes (reflected in the differences of fully cured results), comparisons of indexes obtained were made on a relative basis. This was done by dividing the results of a specific index test by the fully cured result from the appropriate drying regime. Thus all relative 28 day indexes were equal to 1,00, and represented the potential durability of the concretes investigated, when subjected to standard wet curing conditions*. The results obtained from the various drying regimes were interpreted relative to this standard. For any relative index given, the adjusted value** can be obtained by multiplication with the appropriate fully cured result in Table 7-1.

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* Standard wet curing refers to the method prescribed to cure cubes for compressive strength testing [SABS 0100, 1992], and involves submersion of concrete samples for 28 days, at 22-25°C.

** The adjusted experimental values are used during the subsequent discussions (see the introductory paragraph of this chapter), for clear illustrations of the influences of the environmental factors.

In the subsequent discussion the relative indexes are plotted versus temperature. Mean drying temperatures were 18,8, 27,9 and 35,3°C, with accompanying relative humidities of 54,0%, 52,5% and 51,5% respectively.

7.2.1. The influence of temperature on 20 MPa concretes

The relative indexes obtained for the 20 MPa concretes are illustrated in Figure 7-2. Note that the legend refers to the concrete grade and period of wet curing, i.e. 20/1 indicates a 20 MPa concrete, wet cured for 1 day.

The performance of the 20/1 concretes emphasised the crucial role played by wet curing, before exposing these concretes to high temperatures (35°C). Under these conditions, the quality of the poorly cured concretes was much impaired. Extending the curing period to 3 and 7 days resulted in better chloride conductivity and oxygen permeability indexes than at 19°C, while the chloride conductivity of the 20/7 samples were better than those of the fully cured results* . The water sorptivity results of the better cured concretes were still slightly worse at 35°C than at 19°C.

The most apparent feature of the results in Figure 7-2, is the quality these lower concrete grades achieve when drying at 28°C. Except for the 20/1 water sorptivity results, the indexes obtained were better at 28°C than at 19°C. Furthermore, all the results (except for the 20/7 chloride conductivity) were better at 28°C than at 35°C. The oxygen permeability for the 20/7 samples were better than the fully cured results, while the water sorptivity and chloride conductivity results were almost as good.

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* Note that the fully cured results were obtained from concretes cured at *20°C*. Thus, when a 7 day wet cured result is better than the fully cured result, it suggests that the elevated temperature of the drying regime resulted in the development of a *better* pore structure than that achieved by wet curing for 28 days, at 20°C.

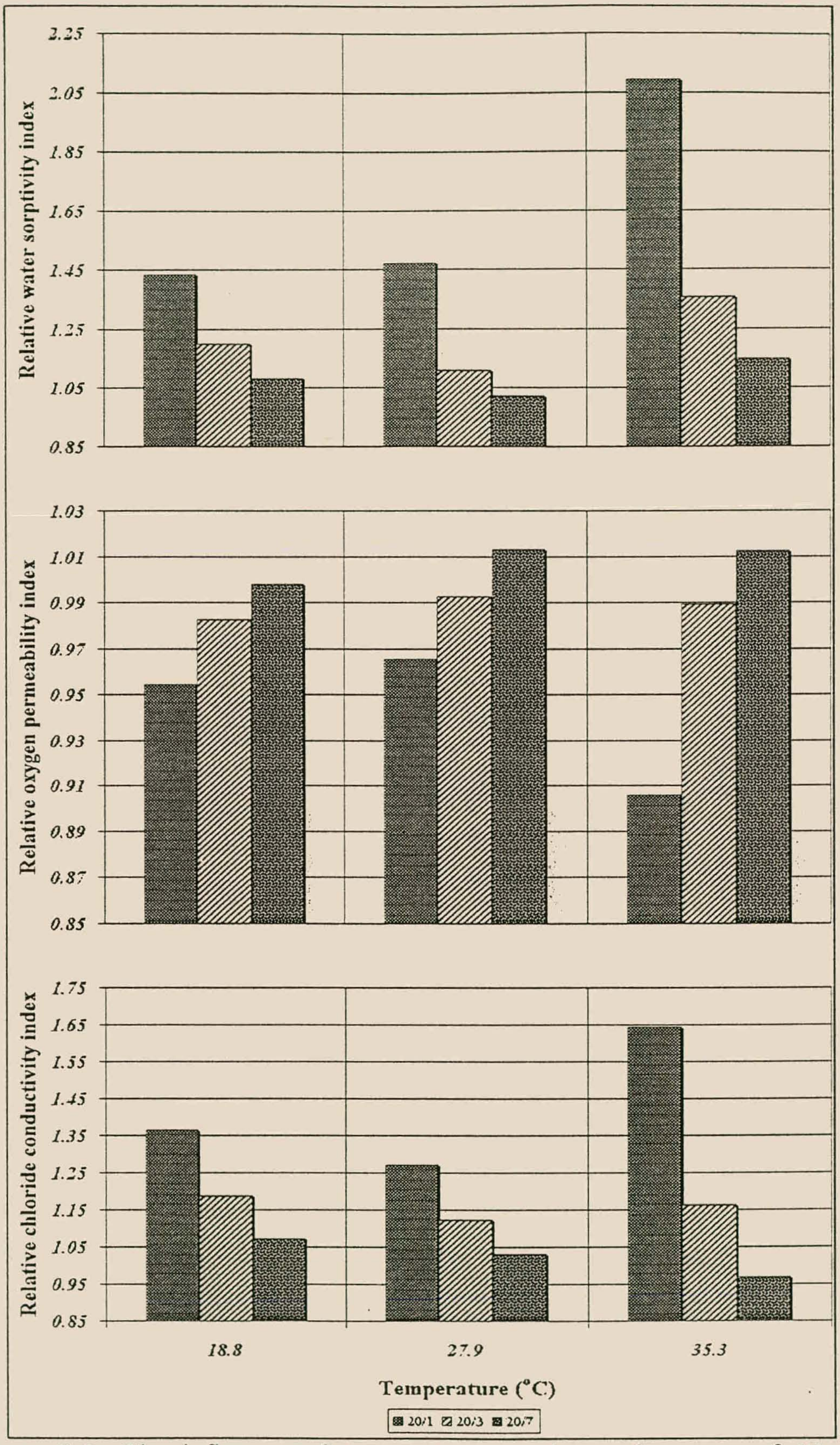

Figure 7-2: The influence of temperature on the performance of 20 MPa concretes

7.2.2. The influence of temperature on 40 and 60 MPa concretes

The relative indexes obtained for the 40 MPa concretes are illustrated in Figure 7-3. The trends of the 60 MPa concretes were almost identical to those observed for the 40 MPa concretes, and are given in Appendix E.

The water sorptivity of the concretes wet cured for 1 day indicated the sensitivity of this parameter to wet curing, especially when post-curing temperatures were high (35°C). When properly cured, this parameter proved to be quite insensitive to variations in exposure temperatures.

Temperature had a marked effect on the oxygen permeability results, more so than the other parameters. This index was best for these concretes when exposed to 28°C, while the worst results were obtained at 35°C. With proper curing and exposure to 28°C, this parameter was equal to or better than the fully cured results. The poor results at 35°C indicated possible microstructural damage, although this was not verified experimentally. The concrete samples might have suffered from thermal shock* when removed from the curing tank (at 20°C) and placed inside the drying regime.

* Rapid changes in temperature differentials across a member.

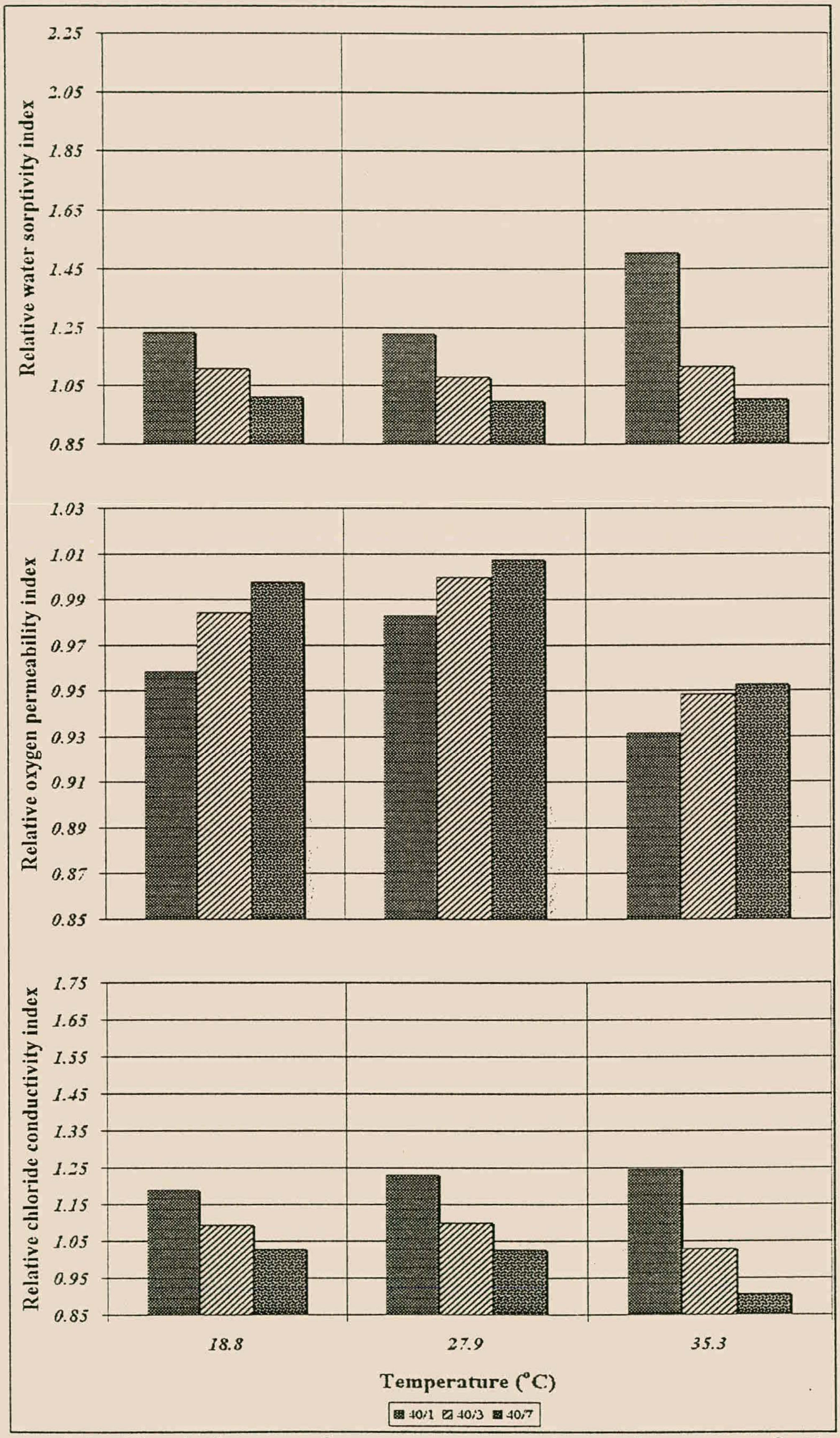

Figure 7-3: The influence of temperature on the performance of 40 MPa concretes

The chloride conductivity results increased with temperature for concretes wet cured for 1 day. For the better cured concretes, this index was almost the same at 19°C and 28°C, and at 35°C improved to values better than fully cured results. This is the opposite of the trend observed for oxygen permeability.

7.3. The influence of relative humidity on the durability index results

Variations in relative humidity had a much less pronounced influence than temperature on the potential durability of the concretes investigated. The trends observed for the results of the three index tests differed, but were similar for all three concrete grades, showing either relative reductions or increases in sensitivity with varying w:c ratio.

Therefore, the results of the three index tests are discussed individually. Scales are kept constant, for illustration of the relative sensitivity of the three concrete grades to changes in relative humidity.

Drying relative humidities were 54,0, 66,0 and 82,0%, with accompanying temperatures of 18,8, 18,0 and 19,1°C respectively.

7.3.1. Water sorptivity

The influence of relative humidity changes on water sorptivity is illustrated in Figure 7-4. When wet cured for 1 day, the water sorptivity of any concrete grade was similar at 54% and 66% RH, with marked improvements at 82% RH. With three days of wet curing, this index improved significantly, and results obtained at 66% RH were slightly better than those at 54% RH. After 7 days of wet curing, relative humidity had virtually no influence on results obtained. The relative sensitivity to wet curing and changes in relative humidity decreased with w:c ratio.

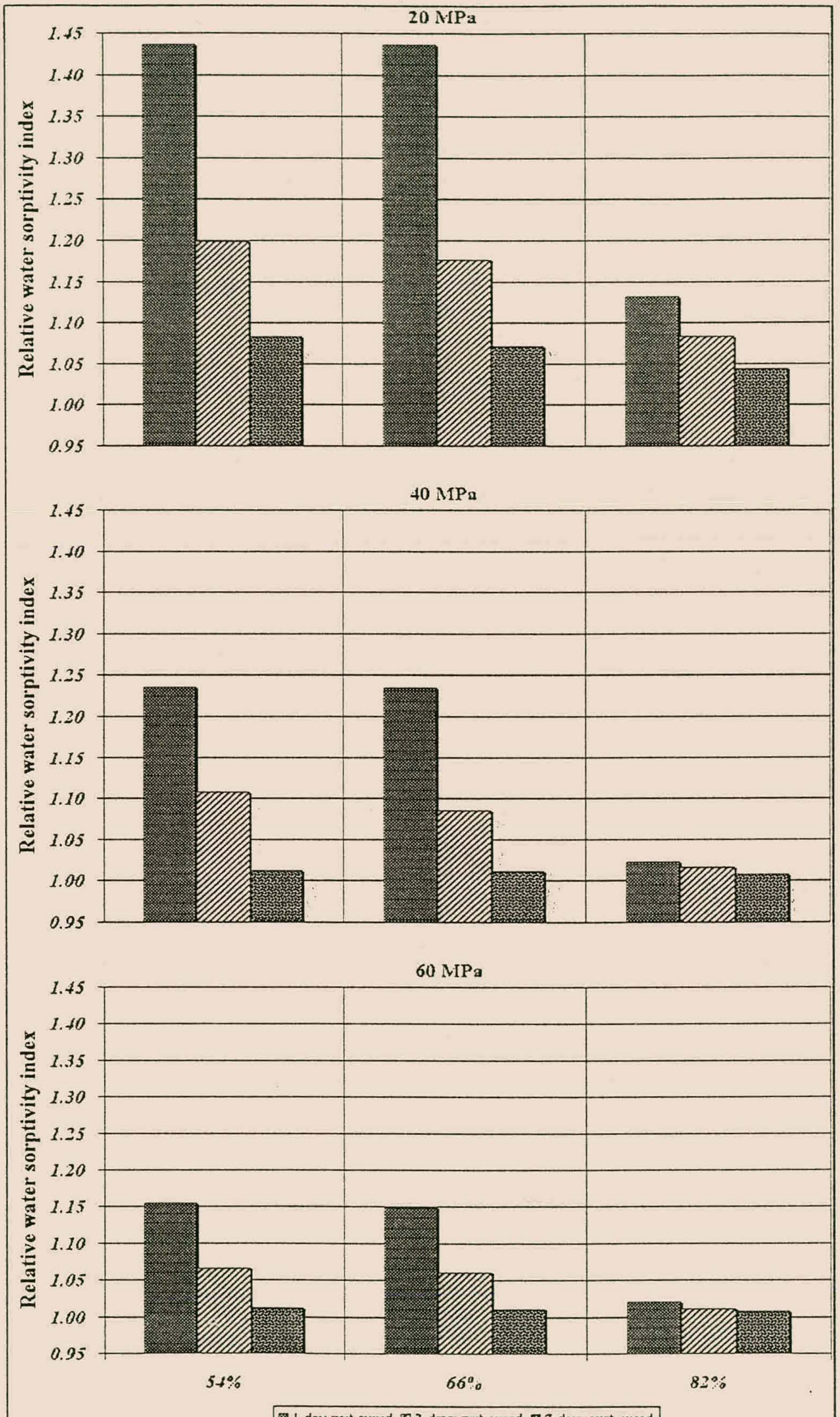

Figure 7-4: The influence of relative humidity on the water sorptivity of 20, 40 and 60 MPa concretes

At 82% RH, the influence of wet curing on this index becomes insignificant, and all results obtained in this drying regime were almost as good as the fully cured results.

7.3.2. Oxygen permeability

The influence of relative humidity changes on oxygen permeability is illustrated in Figure 7-5. This index was not very sensitive to changes in relative humidity. Even after 1 day of wet curing and subsequent drying at 54% RH, the oxygen permeability indexes obtained were more than 95% of the fully cured results. Wet curing for 3 days was quite sufficient for practical purposes, while 7 days of wet curing resulted in oxygen permeabilities very close to those obtained after 28 days of wet curing.

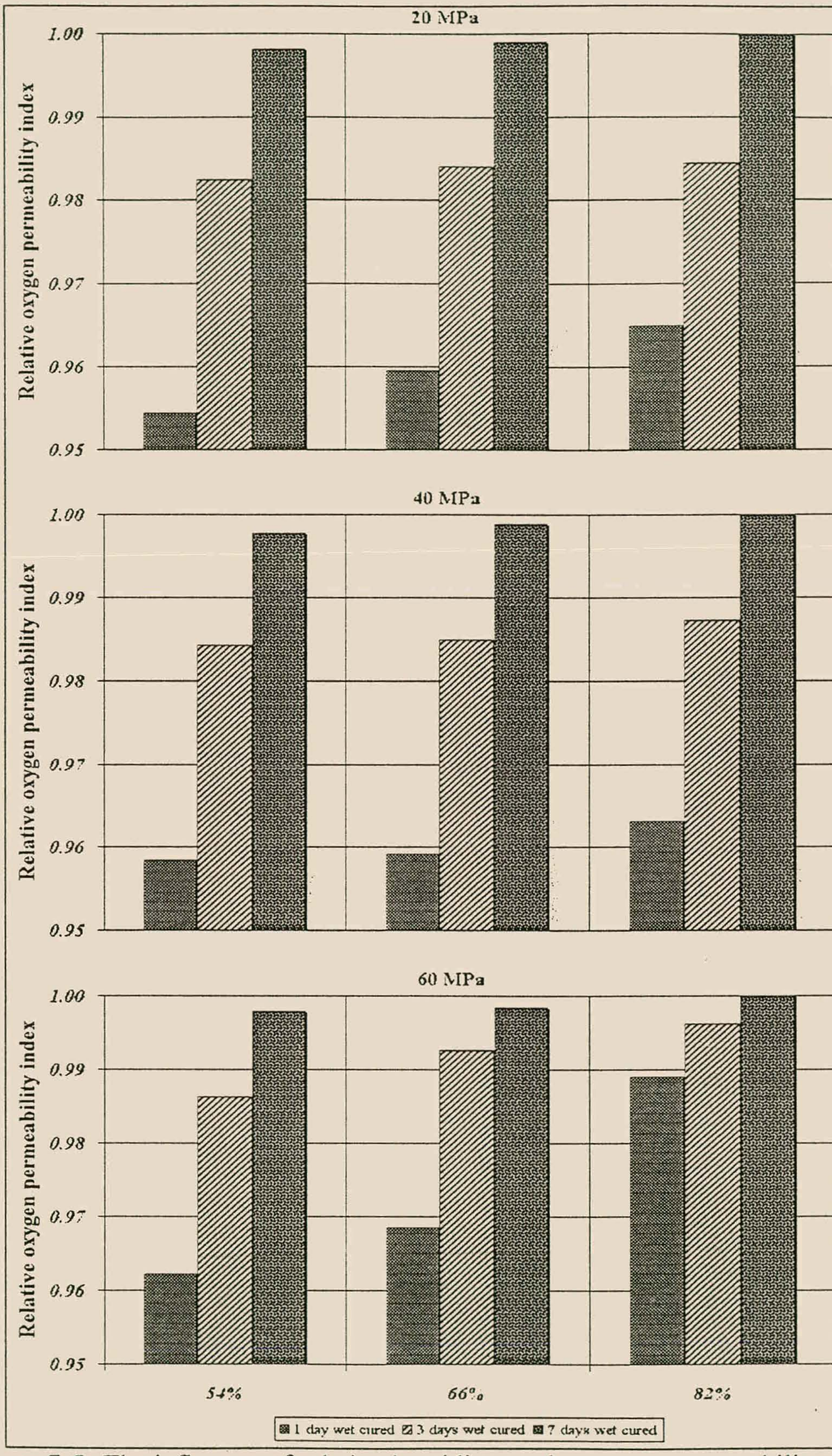

Figure 7-5: The influence of relative humidity on the oxygen permeability of 20, 40 and 60 MPa concretes

7.3.3. Chloride conductivity

The influence of relative humidity changes on chloride conductivity is illustrated in Figure 7-6. Only the 20 MPa concrete seemed to be significantly sensitive to changes in period of wet curing and relative humidity. With 1 day of wet curing, this index improved markedly when drying at 66% instead of 54% RH, with a smaller difference between 66% and 82% RH. The same trend was observed with 3 days of wet curing, while 7 days of wet curing resulted in similar indexes at 54% and 66% RH, with a greater difference between 66% and 82% RH.

The 40 MPa concrete was much less sensitive to relative humidity with changes in period of wet curing than the 20 MPa concrete, and improvements caused by better curing and higher relative humidities were small. The 60 MPa concrete proved to be quite insensitive to both of these parameters, and all indexes obtained were sufficiently close to the fully cured results.

In terms of practical considerations, the influence of wet curing on this index is small at 82% RH. The results obtained for 20 and 40 MPa concretes, with 1 day of wet curing, were typically 14% to 15% poorer than fully cured results. The difference between 1 day of wet curing and fully cured conditions, for the 60 MPa concrete, was less than 5%.

7.4. The influence of wind speed on the durability index results (environment 7)

The preliminary assessment of the influence of wind speed (see section 4.6.1) showed that this parameter was quite insignificant as far as potential concrete durability is concerned. Two concretes were investigated, of which the first was of poor and the other of reasonably good quality (20/1 and 40/7 respectively). In both cases, samples exposed to a constant wind speed of 5,6 m/s (for 22 days) were compared to samples drying in still air, at the same temperature and

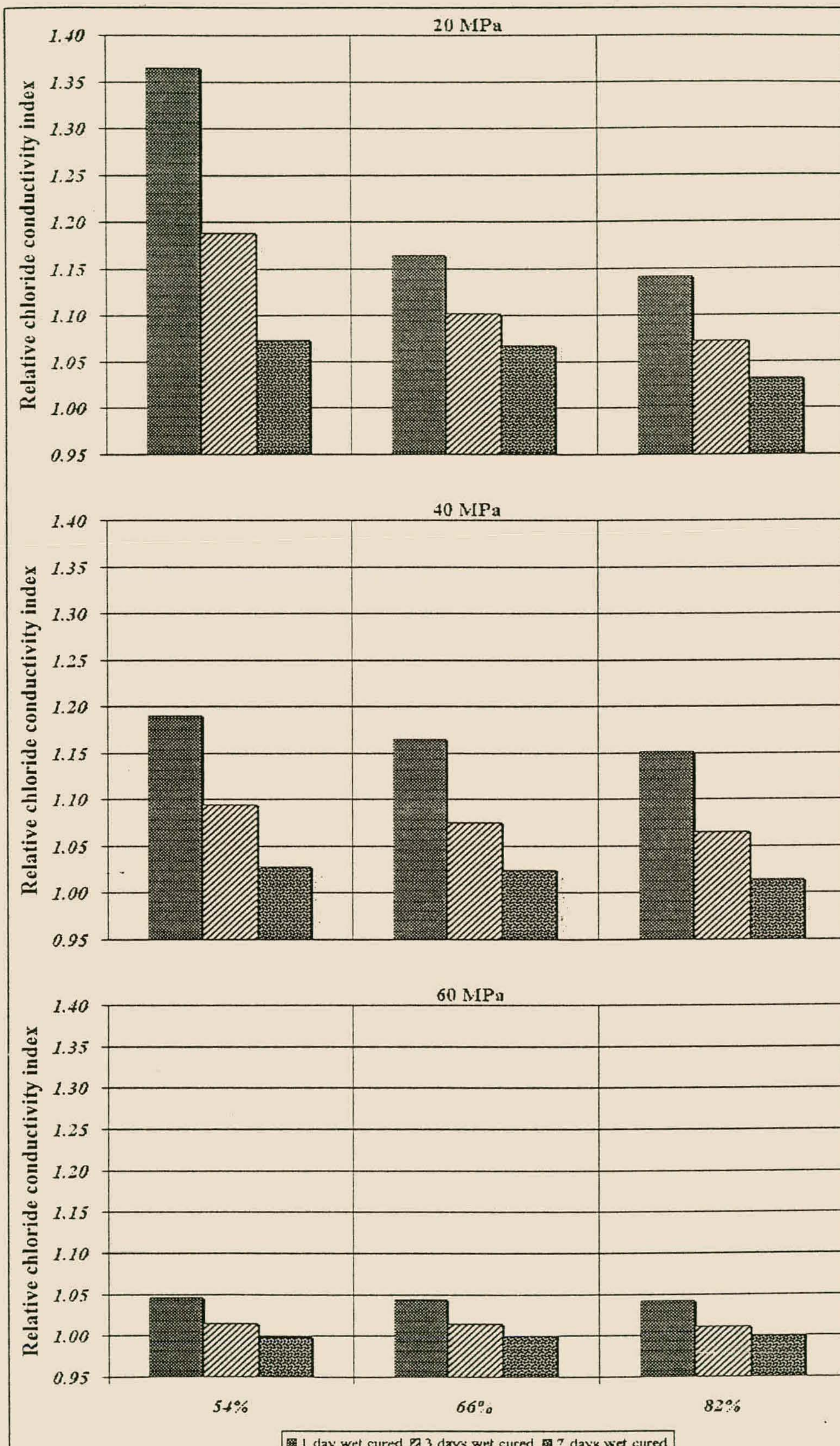

Figure 7-6: The influence of relative humidity on the chloride conductivity of 20, 40 and 60 MPa concretes

humidity. The average temperature and relative humidity were 20,7 °C and 59,5% for the 20/1 samples and 18,6°C and 56,5% for the 40/7 samples.

The indexes obtained are given in Table 7-2, for both the 20/1 and 40/7 samples. The indexes were slightly better for the samples drying in still air. If the general variability of results (in this investigation) is taken into consideration, the conclusion can be made that the influence of wind speed is minor, and negligible for practical purposes.

Table 7-2: Index results obtained from the two wind speed investigations

Index test	20/1		40/7	
	Wind	Still air	Wind	Still air
Water sorptivity (mm/√hr)	22,89	21,35	8,93	8,90
Oxygen permeability index	8,48	8,67	9,95	10,08
Chloride conductivity (mS/cm)	3,76	3,43	2,34	2,09

7.5. The influence of the direction of casting on the durability index results

During the investigations of drying regimes 3, 4, 5 and 6, extra cubes were cast and wet cured for the entire 28 day period. These cubes were cored perpendicular to the direction of casting, in contrast to the samples used during this investigation, which were cored parallel to the direction of casting.

The averages of the index results obtained from these cubes are compared to the averages of the fully cured results retrieved from the concretes cast in baking trays (Table 7-3). The water sorptivity index was most sensitive to the direction of casting, especially for the lower concrete grades. The chloride conductivity was also slightly better for the cubes, while the oxygen permeabilities of the cubes and trays were very similar.

These results indicate that vertical shutter-elements, like columns, walls and the sides of beams, are expected to show a slightly better durability performance than horizontally exposed elements (e.g. slabs).

Table 7-3: Comparisons of fully cured results of samples cored perpendicular (cubes) and parallel (trays) to the direction of casting

Index test	20 MPa		40 MPa		60 MPa	
	Cubes	Trays	Cubes	Trays	Cubes	Trays
Water sorptivity (mm/√hr)	8,21	10,75	7,32	8,69	7,22	8,48
Oxygen permeability index	9,34	9,38	10,16	10,07	10,25	10,33
Chloride conductivity (mS/cm)	2,46	2,57	1,58	1,77	0,99	1,17

7.6. Conclusions

7.6.1. The influence of w:c ratio and period of wet curing

Average durability indexes were obtained from the fully wet cured results (at 20°C) of drying regimes 2 to 6, for the 20, 40 and 60 MPa concretes. These can be used to compare the fully cured performance of the three concrete grades, and as a standard for the calibration and interpretation of the results obtained from the results of this investigation. Potential durability properties ranged from very poor to fairly good.

7.6.1.1. The influence of wet curing on the 20 MPa concretes

Wet curing for at least 3 days seemed to be necessary for these concretes. Extending the curing period to 7 days resulted in an oxygen permeability index similar to fully cured results. The water sorptivity and chloride conductivity indexes still improved markedly when the curing period was extended to 28 days.

7.6.1.2 The influence of wet curing on the 40 and 60 MPa concretes

Wet curing was not as critical for these higher grade concretes, especially for the chloride conductivity index. Three days of wet curing were adequate for performance in terms of the other two indexes. Wet curing for 7 days resulted in similar indexes obtained from the fully cured concretes.

7.6.2. The influence of temperature

7.6.2.1. 20 MPa concretes

- The lower concrete grades were very sensitive to temperature differences. At high temperatures (35°C), lack of wet curing resulted in large decreases in potential durability, while extended curing periods resulted in indexes close to, or even better than fully cured concretes (at 20°C).
- The 28°C environment seemed to provide the best balance (of environments 2, 3 and 4) between rate of moisture loss and increased rates of hydration.

7.6.2.2. 40 and 60 MPa concretes

- The water sorptivity indexes of the 40 and 60 MPa concretes were sensitive to lack of wet curing at high temperatures (35°C). Lack of curing resulted in poor results, while better cured concretes proved to be insensitive to variations in exposure temperatures.
- The oxygen permeability results were best for these concretes when exposed to 28°C, with the worst results obtained at 35°C. With proper curing and exposure to 28°C, this parameter was equal to or better than the fully cured results (at 20°C).
- The chloride conductivity results increased with temperature for the 40/1 and 60/1 concretes. For the better cured concretes, this index was almost the same at 19°C and 28°C, and at 35°C improved to values better than fully cured results.

7.6.3. The influence of relative humidity

7.6.3.1. Water sorptivity

- When wet cured for 1 day, the water sorptivity of any concrete grade was similar at 54% RH and 66% RH, with marked improvements at 82% RH. The sensitivity of this index to relative humidity decreased with w:c ratio and longer periods of wet curing.
- At 82% RH all results obtained were practically identical to the fully cured results.

7.6.3.2. Oxygen permeability

- This index was not very sensitive to changes in relative humidity, irrespective of the curing period involved.
- At 82% RH all results obtained were practically identical to the fully cured results.

7.6.3.3. Chloride conductivity

- Only the 20 MPa concrete seemed to be significantly sensitive to relative humidity, with changes in period of wet curing.
- Improvements caused by better curing and higher relative humidities were small for the 40 MPa concrete.
- The 60 MPa concrete proved to be insensitive to both of these parameters, and all indexes obtained were practically the same as the fully cured results.
- At 82% RH the influence of wet curing was small, but not negligible for the 20 and 40 MPa concretes.

7.6.4. The influence of wind speed

- For both the 20/1 and 40/7 samples, the indexes were slightly better for the samples drying in still air.

- If the general variability of results (of this investigation) is taken into consideration, the conclusion can be made that the influence of wind speed is minor, and negligible for practical purposes.

7.6.5. The influence of the direction of casting

- The water sorptivity index was most sensitive to the direction of casting, especially for the lower concrete grades.
- The chloride conductivity index was also slightly better for the cubes, while the oxygen permeability indexes of the cubes and trays were very similar.

8. Discussion of Results

The results of Chapter 6 and Chapter 7 can be used to interpret the importance of the different environmental factors on the potential durability of concrete. The two components of the results are:

1. The moisture losses from concretes drying under various environmental conditions.
2. The durability index results obtained from these concretes.

These two components are related [Parrot, 1991], and can be used in combination to examine the influences of temperature, relative humidity and wind speed on the development of covercrete properties. The importance of wet curing, before exposure to different environmental conditions, will also be addressed.

The final part of this chapter is based on work done by Parrott [1991] (see section 2.3.2.1), during which broad correlations were found between initial moisture loss and covercrete properties. The controlled conditions of the present investigation provided sufficient experimental data to explore this concept, and can be used for a better understanding of the effect of initial moisture loss on the potential durability of concrete.

8.1. The influence of temperature on the potential durability of concrete

Of the three types of environmental factors investigated, temperature had the most significant influence on the results obtained. Depending on the concrete quality (in terms of w:c ratio and period of initial wet curing) the concretes investigated either benefited from more rapid hydration rates, or was impaired by the rapid evaporation rates of elevated temperatures.

8.1.1. Comparison of trends observed from moisture losses and the index results

The relationship between moisture loss and temperature, for 40 and 60 MPa concretes, is illustrated in Figure 8-1. Note that the line for 60 MPa concretes, wet cured for 3 days (see point 2. in 6.3), was omitted from this curve, in order to illustrate the apparent trend of the influence of temperature on moisture loss from reasonable (40/1) to good (60/7) quality concretes.

The influence of w:c ratio and period of wet curing is evident in this figure. Less moisture was lost from concretes with lower w:c ratios and longer periods of initial wet curing, and indicates denser pore size structures. The noteworthy observation that can be made from this figure, is the relative similarities in sensitivity to temperature changes. This is reflected in the similar slopes of the lines for the different concretes, and implies that the 40 and 60 MPa concretes should show similar trends when exposed to different temperatures.

The moisture losses of the 20 MPa concretes, on the other hand, showed somewhat different trends, as illustrated in Figure 8-2. Significant increases in moisture loss was observed towards 35°C, especially for poorly cured concretes. This indicates that this poorer quality concrete is much more sensitive to exposure to elevated temperatures, and suggests poor performance in terms of the index results under such conditions.

These trends were confirmed with the indexes obtained from the temperature environments (drying regimes 2, 3 and 4). The oxygen permeability indexes can be used as typical illustration, as is done in Figure 8-3. The trends of the 40 and 60 MPa concretes were very similar, but differed from the trends observed for the 20 MPa concretes. Also apparent in this figure, is the sensitivity of the 20 MPa concrete to initial wet curing, which is consistent with the trends of the trends of the moisture losses of Figure 8-2.

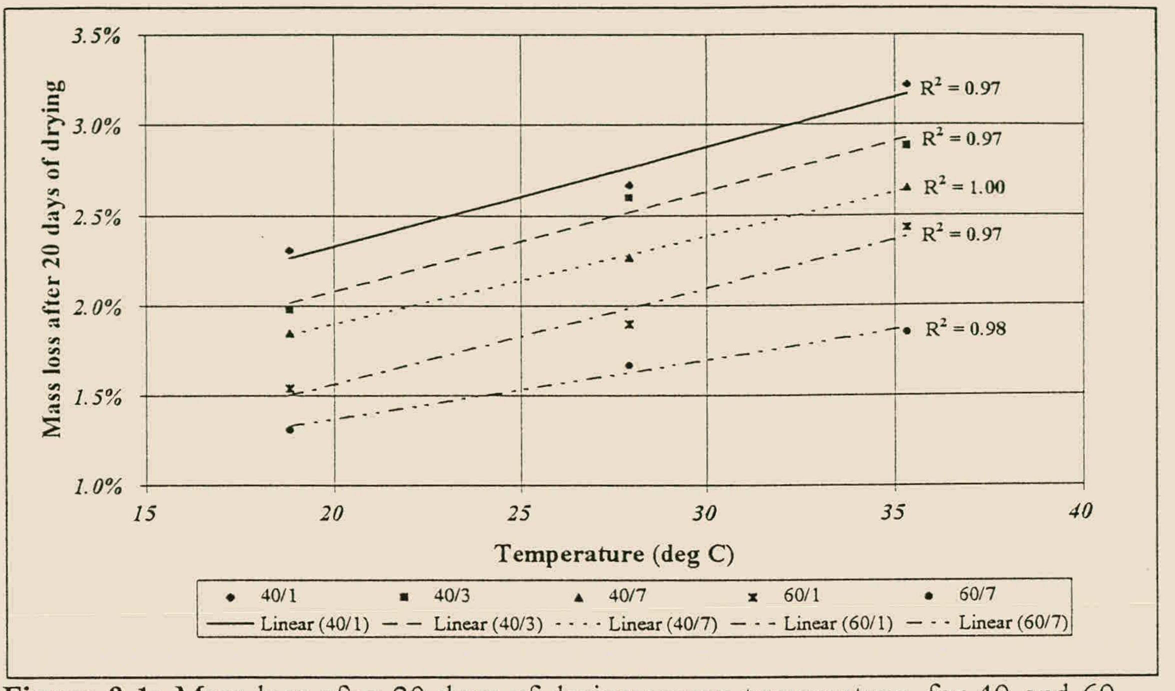

Figure 8-1: Mass loss after 20 days of drying versus temperature, for 40 and 60 MPa concretes

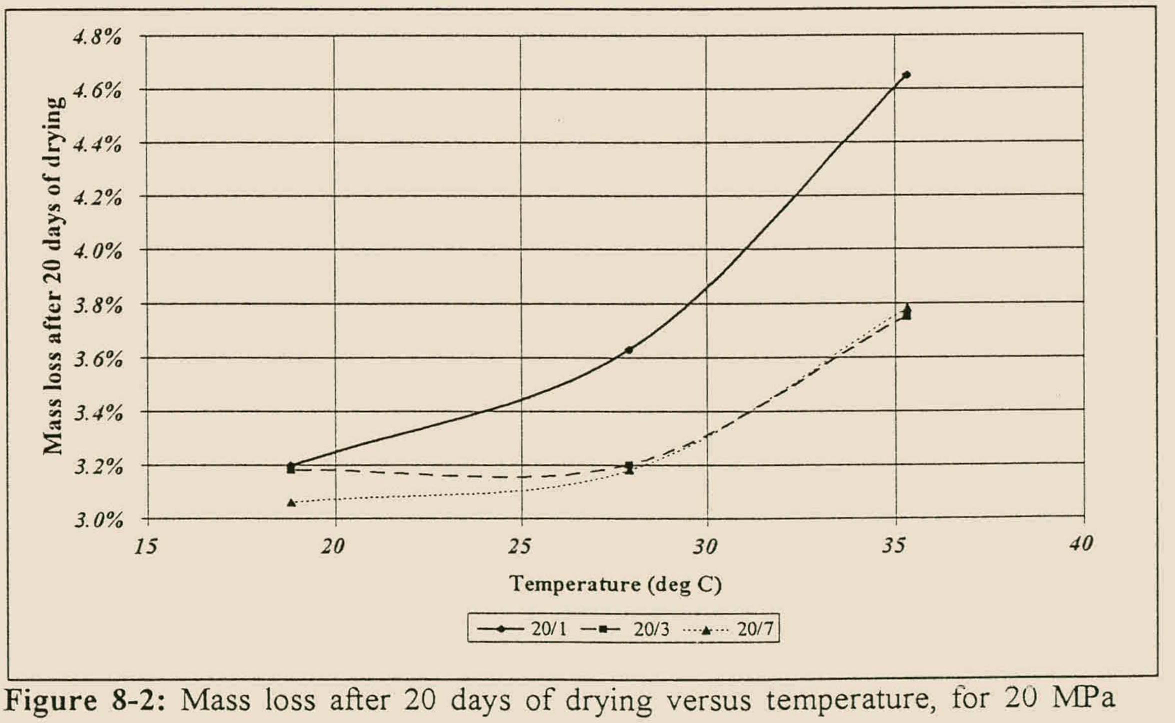

Figure 8-2: Mass loss after 20 days of drying versus temperature, for 20 MPa concretes

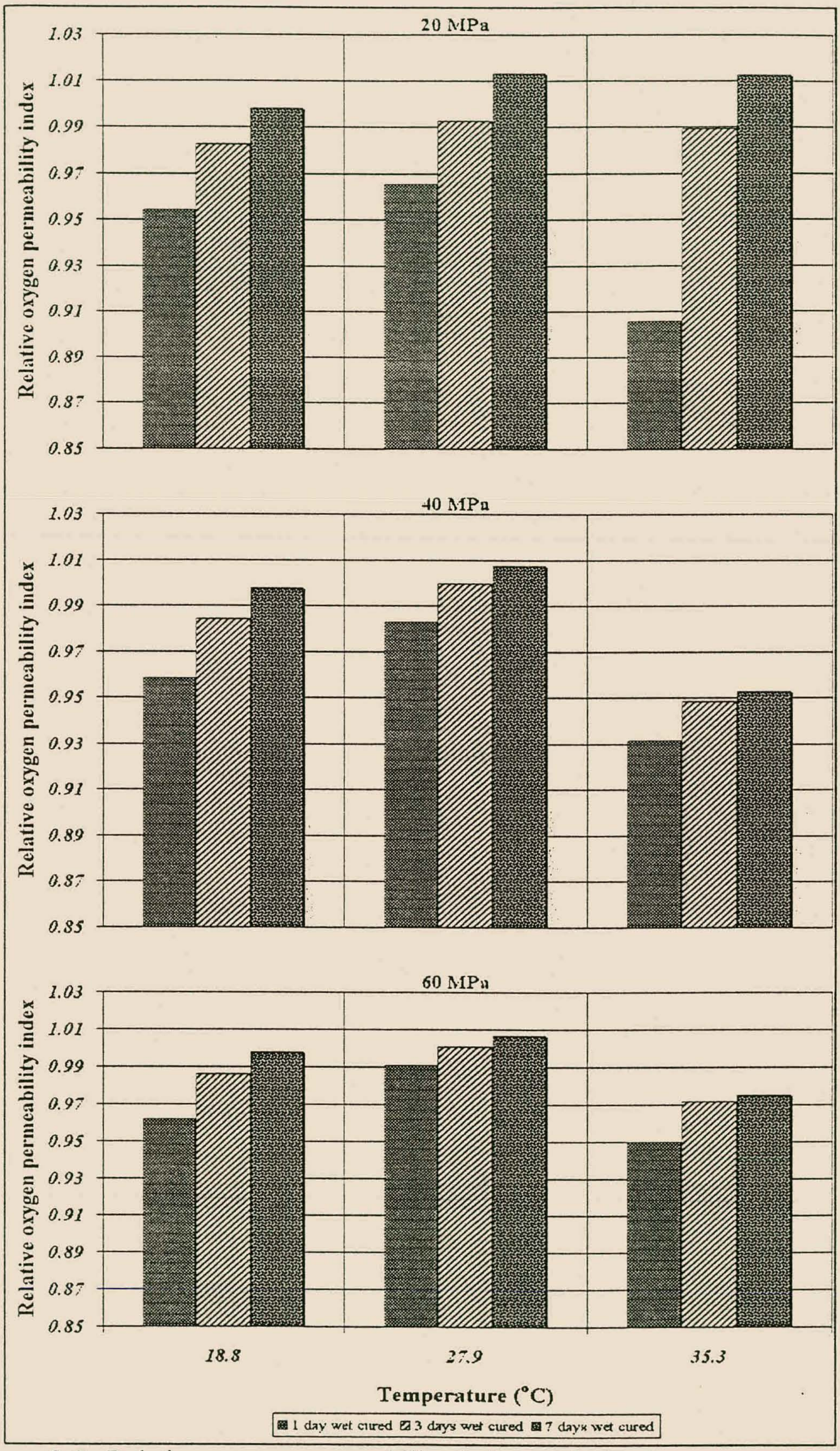

Figure 8-3: Relative oxygen permeability indexes obtained versus temperature, for 20, 40 and 60 MPa concretes

8.1.2. The importance of temperature for potential concrete durability

Temperature had a considerable influence on the durability index results. In the case of poor quality concretes, elevated temperatures (35°C) significantly reduced the quality of the covercrete. On the other hand, concretes with lower w:c ratios and proper initial curing seemed to benefit from the higher temperatures.

These effects can be ascribed to the combined effect of temperature on the rates of hydration and evaporation. A concrete which was adequately cured can resist the influence of faster evaporation rates by retaining its moisture, and benefit from the increased rate of hydration. A poorly cured concrete, on the other hand, loses its moisture rapidly at high temperatures, resulting in poor development of the covercrete properties. As a result of this, wet curing of at least 3 days was essential for all three concrete grades, when exposed to 35°C.

The beneficial influence of elevated temperatures was evident in a significant amount of indexes obtained, when concretes were wet cured for 7 days before the start of exposure. In many cases, indexes obtained after proper curing and exposure to 28°C and 35°C, indicated better or similar covercrete quality than that achieved by wet curing at 20°C for 28 days.

Results obtained from the 28°C drying regime indicated this be the optimum temperature investigated. This was especially evident in the performance of poorly to reasonably cured concretes (1 day and 3 days), which generally showed better quality than that achieved by exposure to 20°C and 35°C.

8.2. The influence of relative humidity on the potential durability of concrete

The influence of relative humidity on the durability indexes was much less significant than temperature. Results obtained at 54% and 66% were generally similar, with significant improvements at 82% RH.

8.2.1. Comparison of trends observed from moisture losses and the index results

The moisture losses versus relative humidity (after 20 days of drying), of poorly cured (1 day) and well cured (7 days) concretes, are illustrated in Figure 8-4. The trends are similar for the three concrete grades, reflected in the shapes of the curves for, for example, the 20/1, 40/1 and 60/1 concretes. There seems to be a significant reduction in moisture loss towards 82% RH, a trend also reflected in the durability indexes obtained.

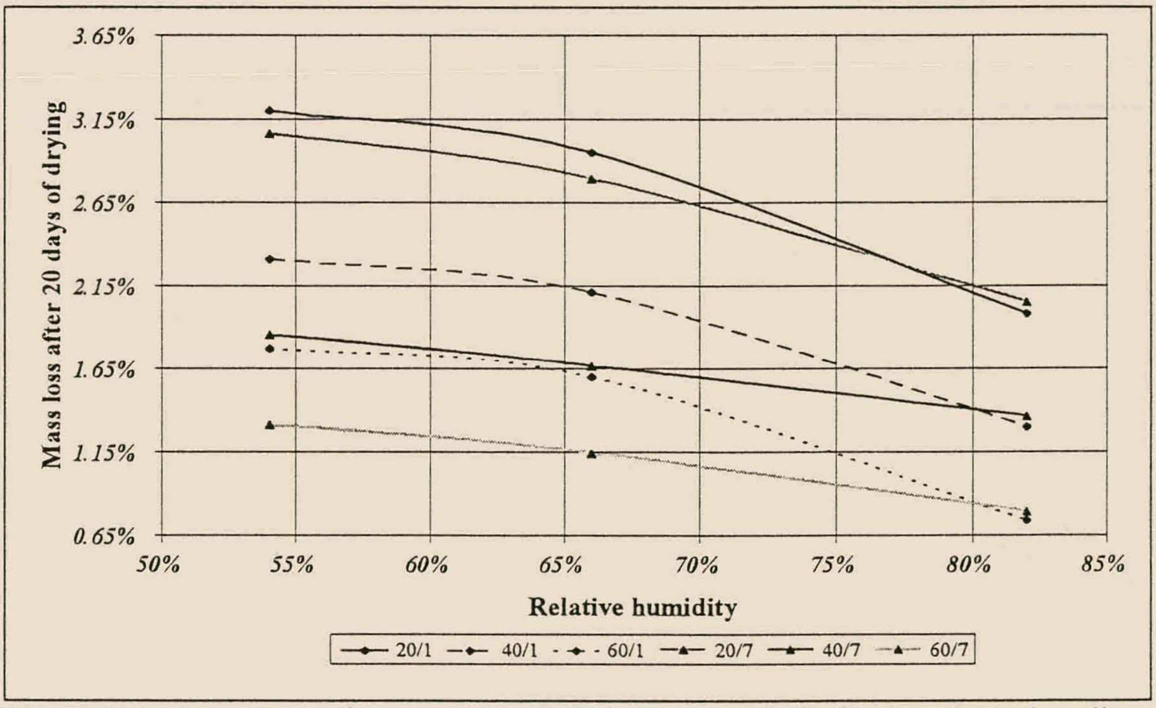

Figure 8-4: Mass loss after 20 days of drying versus RH, for poorly and well cured concretes

As an example, the water sorptivity results for the three concrete grades are illustrated in Figure 8-5. The trends for all three grades were similar, with similar results obtained at 54% and 66% RH, and significant improvements towards 82% RH.

8.2.2. The importance of relative humidity for potential concrete durability

Relative humidities below 80% did not significantly influence durability indexes obtained. At 82% relative humidity, moisture losses decreased and the durability indexes improved markedly. These findings are consistent with work previously done, during which it was concluded that the effect of wet curing becomes negligible under such humid conditions [Patel et al, 1988; Powers, 1947].

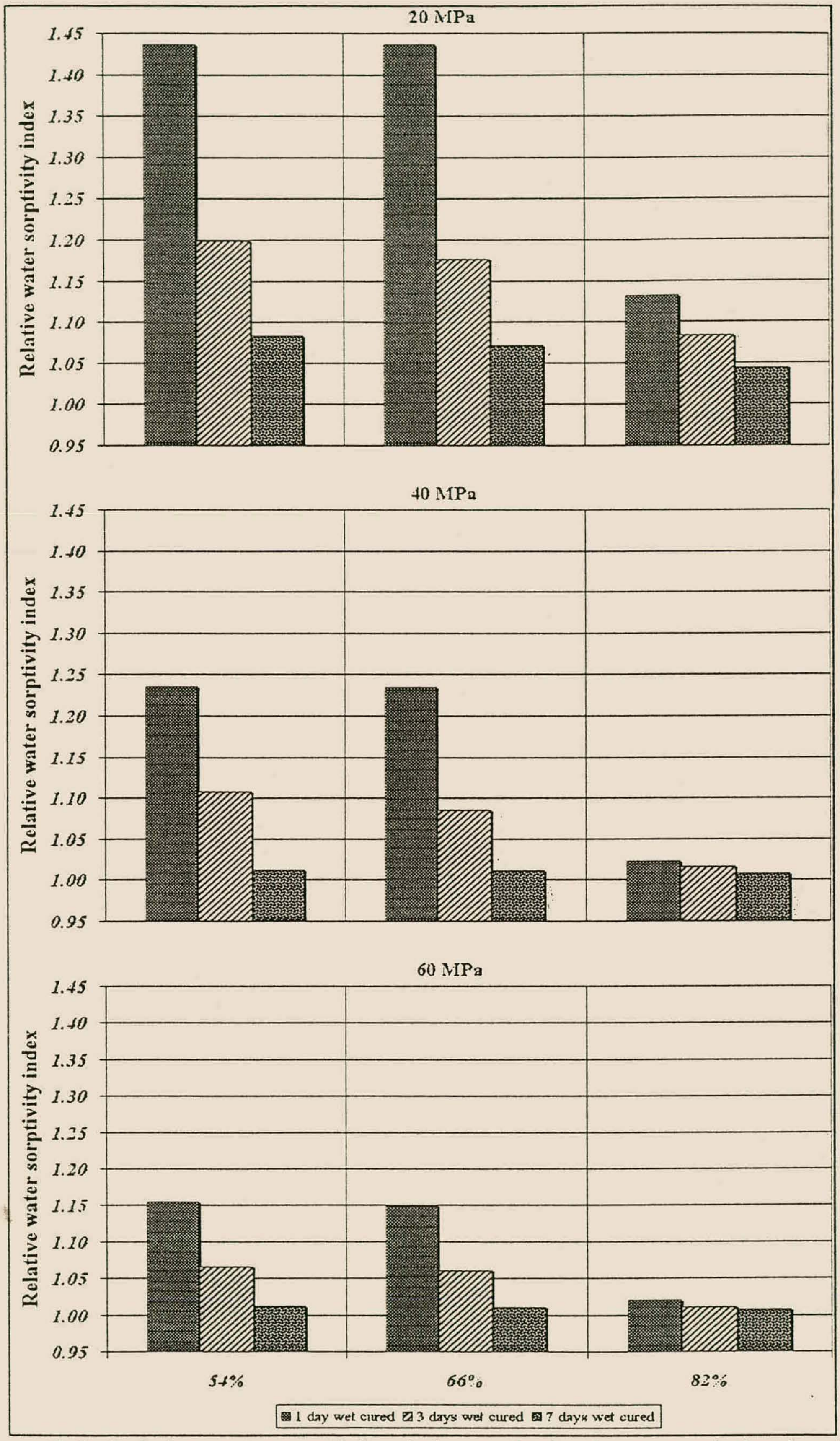

Figure 8-5: Relative water sorptivity indexes obtained versus relative humidity, for 20, 40 and 60 MPa concretes

8.3. The influence of wind speed on the potential durability of concrete

Wind speed had a minor influence on moisture loss and the durability index tests.

8.3.1. Comparison of trends observed from moisture losses and the index results

The moisture losses of the two wind speed investigations are given in Figures 8-6 and 8-7, for the investigations of poorly cured 20 MPa concretes, and well cured 40 MPa concretes respectively. The differences in moisture loss between samples under controlled wind and samples in still air were small, and more so for the 20 MPa concretes than for the 40 MPa concretes. The results of the durability index tests were consistent with the moisture losses, and are given in Table 8-1.

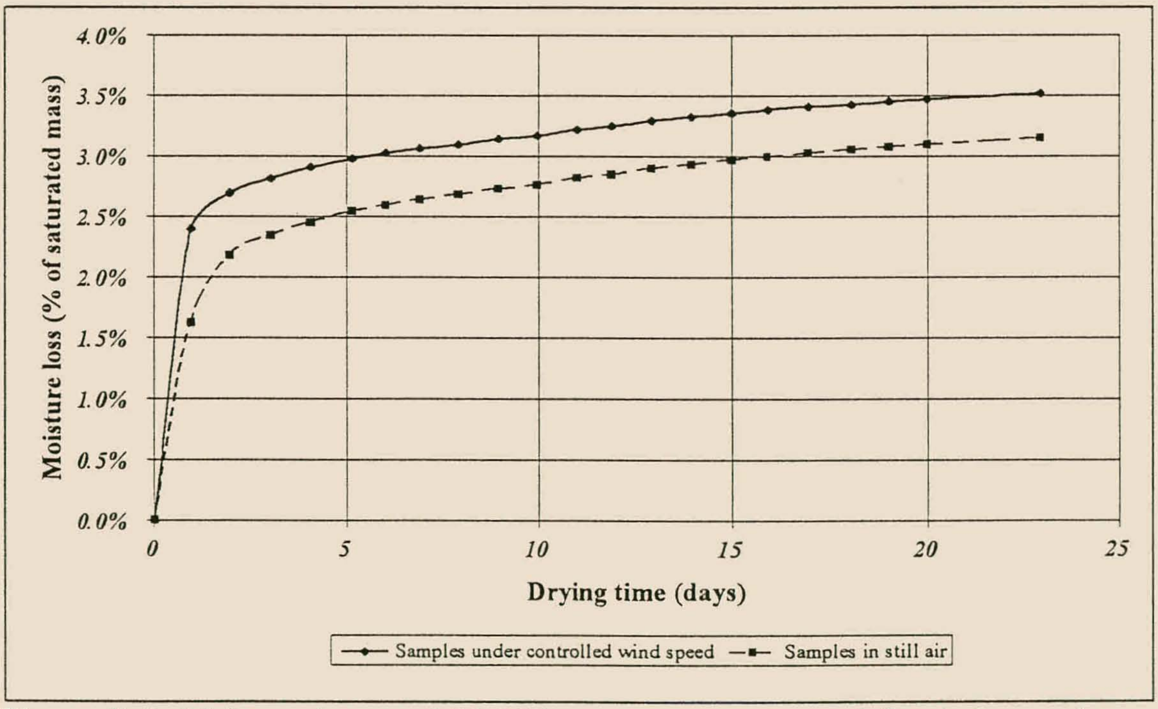

Figure 8-6: Moisture losses of 20 MPa concretes, wet cured for 1 day, under controlled wind and still air conditions

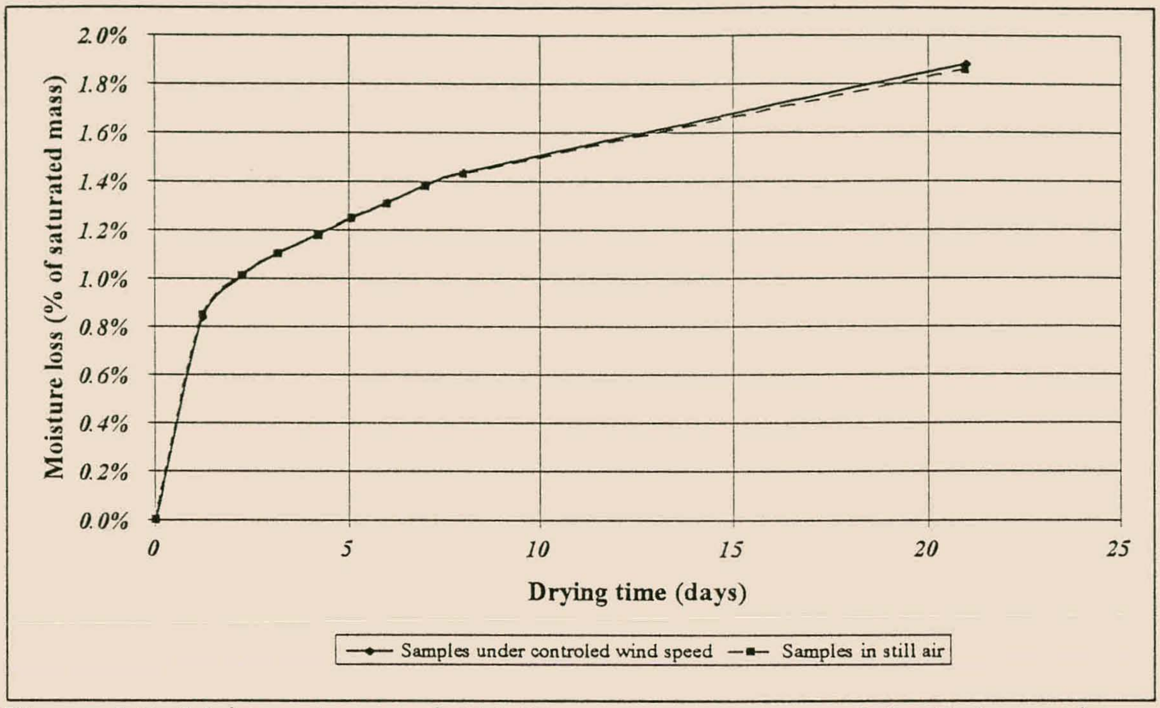

Figure 8-7: Moisture losses of 40 MPa concretes, wet cured for 7 day, under controlled wind and still air conditions

Table 8-1: Durability index results from the two wind speed investigations

Index test	20/1		40/7	
	Wind	Still air	Wind	Still air
Water sorptivity (mm/√hr)	22,89	21,35	8,93	8,90
Oxygen permeability index	8,48	8,67	9,95	10,08
Chloride conductivity (mS/cm)	3,76	3,43	2,34	2,09

8.3.2. The importance of wind speed for potential concrete durability

The conclusion can be made that wind speed does not significantly influence the drying processes of hardened concrete, or the development of its pore structure. Possibly the most important reason for this lies in the mechanisms governing the evaporation of moisture and transportation to the concrete surface.

In hardened concrete, moisture in capillaries is retained by means of moderate surface tension forces [Mindess and Young, 1988] and can only evaporate when the pore relative humidity (at a specified temperature) has dropped sufficiently low [Soroka, 1979]. The water vapour diffuses to the surface along available paths, of which the degree of interconnection of capillaries is probably the most important, as far as differences in moisture loss from concretes of varying quality are concerned.

At a w:c ratio of 0,35 the bulk volume of the cement gel will be sufficient to fill all the empty spaces and produce a cement paste free of capillary pores [Verbeck, 1978]. Higher w:c ratios will result in a large volume of capillary pores, almost continuously distributed through the HCP. At w:c ratios lower than 0,70 and sufficient wet curing, these can become filled and isolated, but above this ratio no amount of wet curing will be sufficient to fill the capillaries [Verbeck, 1978].

Therefore, the capillaries in the 20/1 concrete, especially close to the surface, were almost continuous, due to the high w:c ratio and poor curing. Thus the accelerated evaporation of moisture on the concrete surface, as a result of wind, was directly linked to available moisture at deeper regions. The result was larger initial moisture losses along the continuous paths of interconnected capillaries to the surface of the concrete.

After the first 24 to 48 hours of drying, the drying front had penetrated into the better quality regions of the concrete. Capillaries are less continuous at these depths, breaking the link with the influence of wind speed on the surface, and moisture losses from there onwards were analogous with those of the samples drying in still air.

The 40 MPa concrete had a w:c ratio of 0,56 and was well cured, indicating a well-developed covercrete with capillaries much more isolated than in the case of the poorer quality concrete. The influence of wind speed at the surface of the concrete was not linked to moisture at deeper regions and did not result in greater moisture losses.

8.4. The relationship between moisture loss and durability indexes obtained

Initial moisture loss of concrete is greatly influenced by the w:c ratio of the concrete, the period of wet curing and ambient temperature and relative humidity. According to Parrott [1991], there is a broad correlation between these losses and concrete properties such as water absorption and air permeation.

The results of this study provided enough information on this point to formulate a relationship between initial moisture losses and chloride conductivity, oxygen permeability and water sorptivity.

In Parrott's work [1991], he found that the weight loss measured after 4 days of drying was indicative of water diffusion rates in the covercrete of depths up to 30 mm. The initial rate of weight loss increased with an increase in w:c ratio, shorter periods of wet curing, exposure to drier conditions and partial replacement of Portland cement with fly ash and slag. He found that initial moisture losses correlated broadly with the water absorption rate, air permeability and carbonation depth of concretes subjected to a broad range of drying conditions.

Using this information as reference, the 3 day moisture losses from all concretes drying under different environmental conditions were plotted against the results obtained from the durability index tests. These are shown in Figures 8-8 to 8-10.

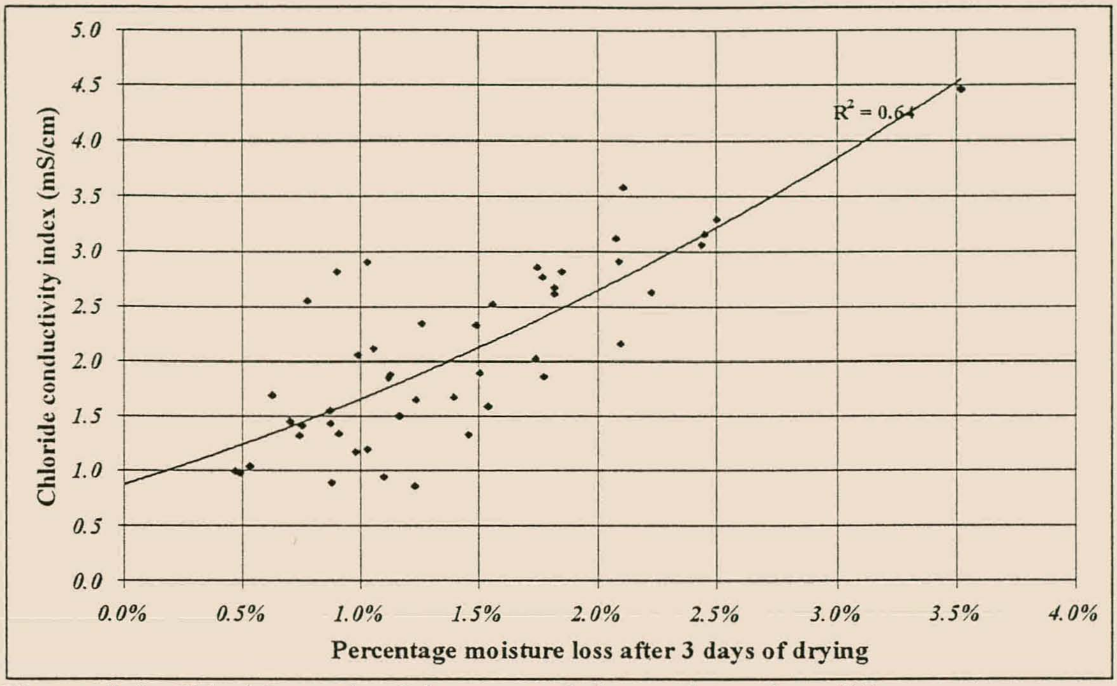

Figure 8-8: Chloride conductivity versus 3 day moisture loss (%)

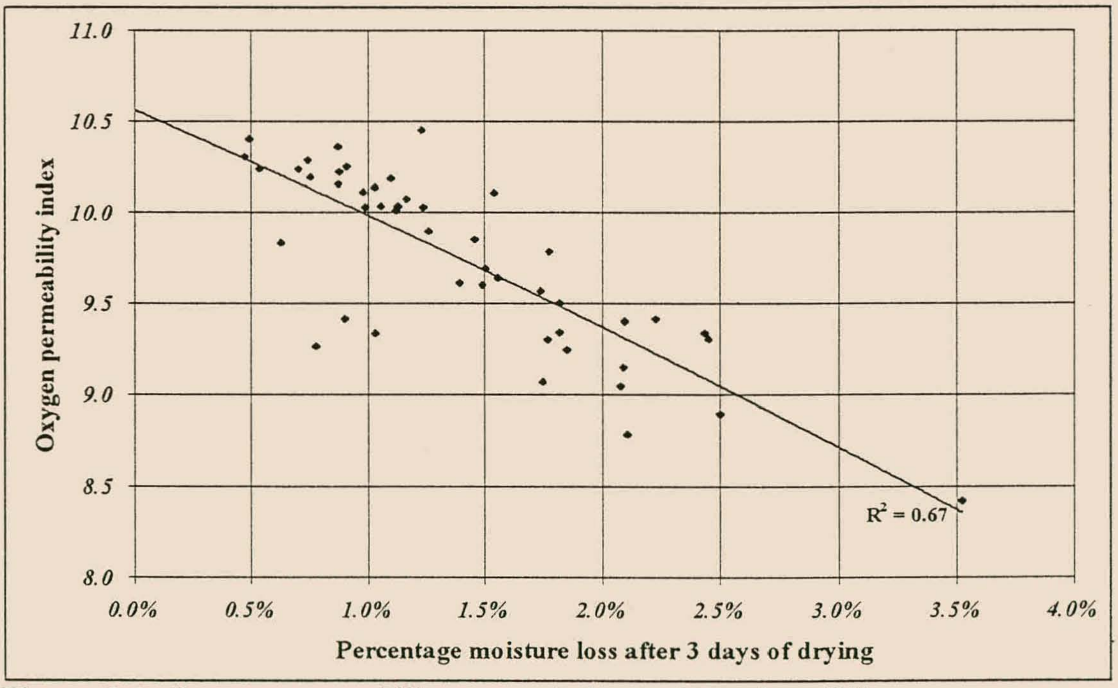

Figure 8-9: Oxygen permeability versus 3 day moisture loss (%)

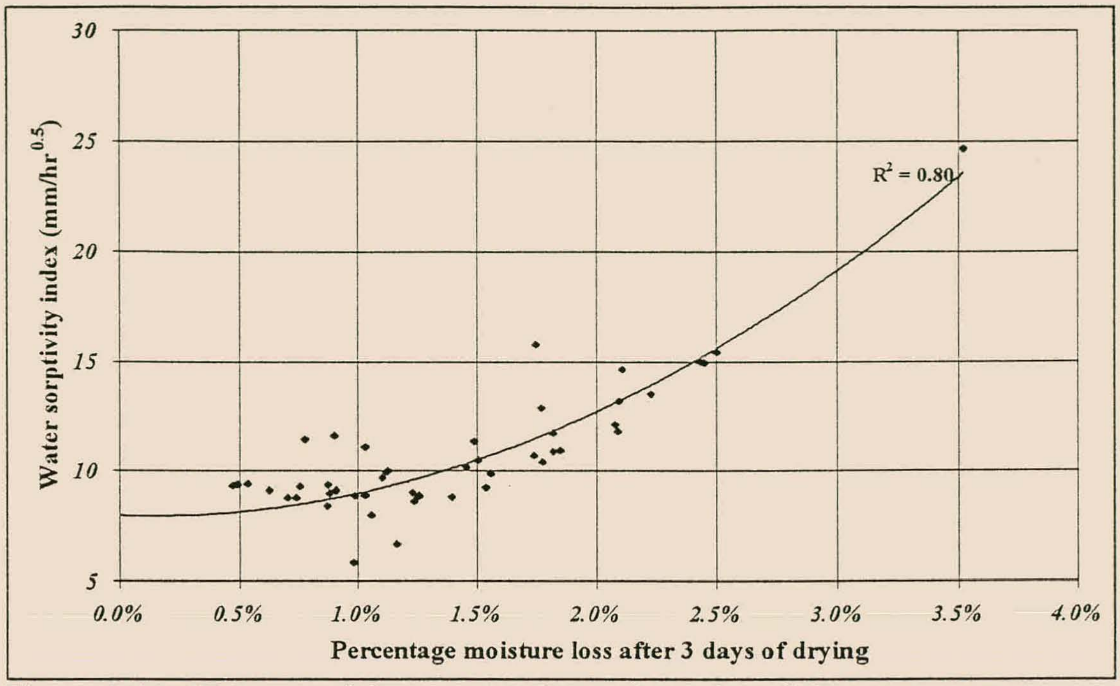

Figure 8-10: Water sorptivity versus 3 day moisture loss (%)

Polynomial trend lines proved to be the best fit for the data, with R^2-values ranging from 0,64 to 0,80. These results are consistent with Parrott's [1991] findings, i.e. broad correlations between initial moisture losses and covercrete properties.

The scatter in the chloride conductivity and oxygen permeability results was more profound than that of the water sorptivity. A possible explanation for this is that 3 days of drying is too short a period on which to make these comparisons. Moisture losses are an indication of emptied capillary porosity, and after 3 days of exposure the depth of drying has not penetrated through the entire depth of concrete that would eventually be subjected to durability testing. Since the samples used for the durability index tests were 25 mm in thickness and the outer 5 mm had been removed during the preparation of the sample, the assumption states that the depth of drying at 3 days would be less than 30 mm from the exposed surface. This meant that hydration was still in progress, and thus the durability properties were still significantly changing after 3 days of drying.

The water sorptivity index, on the other hand, is more sensitive to the outer regions of the concrete, as water penetrates typically between 8 and 15 mm into the concrete during a sorptivity test. Thus this index would be more sensitive to the capillary porosity in this region of the concrete, and would show a better correlation with the 3 day moisture losses.

The information supplied by the Figures 8-8 to 8-10 indicate that the durability indexes are functions of the capillary porosity of the sample being tested. This concept is further explored in the next chapter, where a theory for the drying of concrete is formulated.

8.5. Conclusions

8.5.1. The relationship between initial moisture loss and the durability indexes obtained

For temperature, relative humidity and wind speed, there were definite correlations between initial moisture losses and the durability indexes obtained. In general, the trends observed for moisture loss versus the appropriate environmental factor, were similar to those obtained for the durability index tests.

These similarities were confirmed when the index results were plotted against 3 day moisture losses. The correlations between initial moisture loss and the chloride conductivity and oxygen permeability index results were similar, while water sorptivity showed a significantly better relationship. The reason for this is possibly because water sorptivity is a function of the outer region of the covercrete, while the other two indexes are dependent on the capillary porosity of the entire sample.

8.5.2. The influence of environmental conditions on the durability indexes obtained.

8.5.2.1. Temperature

Temperature had a large influence on the durability index results. In the case of poor quality concretes, elevated temperatures significantly reduced the quality of the covercrete. On the other hand, concretes with lower w:c ratios and proper initial curing seemed to benefit from the higher temperatures. This was due to the combined effect of temperature on the rates of hydration and evaporation. As a result of this, wet curing of at least 3 days was essential for all three concrete grades, when exposed to 35°C.

The indexes obtained at 28°C seemed to be of consistent good quality, indicating that this temperature generally provides good conditions for concreting.

8.5.2.2. Relative humidity

Relative humidities below 80% did not significantly influence durability indexes obtained. At 82% relative humidity, moisture losses decreased and the durability indexes improved markedly. This suggests that the effect of wet curing becomes negligible under such humid conditions.

8.5.2.3. Wind speed

Wind speed did not significantly influence the drying processes of hardened concrete, or the development of its pore structure. Possibly the best explanation for this is that wind cannot 'penetrate' the concrete surface, like temperature and relative humidity. Moisture can only evaporate at faster rates for as long as the drying front is situated within a concrete region with continuous capillary pores.

9. The Durability Indexes Related to the Drying of Hardened Concrete

The previous chapters presented the impact of environmental conditions on the durability indexes of OPC concretes of a certain quality (in terms of grade and period of wet curing). The results of the index tests indicated significant variations in covercrete quality, when exposed to different temperatures and relative humidities.

The component of concrete accountable for these variations is the hardened cement paste. Differences in exposure conditions influence the rate of moisture loss, the degree of hydration at various concrete depths and the subsequent development of the cement paste properties. The objective of this chapter is to present a model for these processes and relate the cement paste properties to the durability index results of chapter 7.

9.1. Summary of a mathematical model for the drying of concrete

Exposure of young concretes to the environment causes evaporation of pore water. This introduces an internal relative humidity gradient with depth into the concrete, and moisture is transported to exposed surfaces by means of surface diffusion, vapour diffusion and capillary action [Hearn et al, 1994]. The rates of these processes are influenced firstly by the severity of the environment, and secondly by the ability of the concrete to retain its moisture.

More severe exposure conditions, in terms of ambient temperature and relative humidity, cause more rapid evaporation, while denser pore structures (lower w:c ratios and longer periods of initial wet curing) resist the transport of moisture to exposed surfaces. Furthermore, the extended availability of sufficient moisture at deeper concrete regions results in continued hydration and improvement of cement paste properties.

The rate of hydration is also influenced by temperature [Soroka, 1979]. For as long as sufficient moisture is available at any particular concrete depth, higher temperatures cause more rapid hydration and increase the rate of the development of covercrete properties.

In the formulation of the subsequent theory, the influence of drying processes is regarded in terms of decrease in pore relative humidity and the resulting development of the porosity characteristics of the cement paste. Parrott [1988] and Patel et al [1988] established that hydration rates are very sensitive to changes in pore relative humidity. Furthermore, it was observed by them that significant changes in porosity of the cement paste take place above 95% pore relative humidity, and continued hydration below this value has only minor influences in the development of the pore structure (see section 2.3.3.1.2). In the context of this theory, what is important will be that hydration at pore relative humidities higher than 95% significantly affects the porosity characteristics of the cement paste.

The total porosity of the cement paste is equal to the sum of the capillary and gel porosities. However, the gel pores are very small (typically smaller than 4 nm diameter [Patel et al, 1988]), and although the gel porosity contributes to a significant part of the total porosity, capillary absorption, permeability and diffusion processes occur primarily in the larger capillary pores [Hearn et al, 1994]. Therefore, the assumption is made that the durability indexes are primarily a function of the capillary porosity of the cement paste, and insensitive to the influence of gel porosity.

The model can be divided into the following steps:

- Calculation of the period of time, at any depth into the concrete, for which pore relative humidities are ≥ 95%. This period of time can be added to the initial curing period, and an effective curing period calculated.
- Calculation of the effective degree of hydration, as a function of w:c ratio and the effective curing period.
- Calculation of capillary porosity, as a function of w:c ratio and effective degree of hydration.
- Relation of the capillary porosity characteristics to the durability indexes obtained during this investigation. It was found that the *average capillary porosity* of the cement paste can be related to the chloride conductivity and oxygen permeability indexes, while the water sorptivity proved to be a function of the *capillary volume* in the outer regions of the covercrete.

9.1.1. Limitations

The scope of the research done during this investigation did not include the measurements of pore relative humidities, degree of hydration or the porosity characteristics of the cement paste. Thus the theory formulated is based on information, assumptions and empirical formulae derived by other researchers, and has the following limitations:

- The degree of hydration of hardened cement paste is a complex function of the fineness of the cement, its chemical composition, w:c ratio, time and temperature. For the purposes of this discussion, the degree of hydration is approximated with empirical formulae, derived from Figure 9-1 [Soroka, 1979]. In this figure, the degree of hydration is given as the amount of chemically bound water, i.e. the w_n:*c* ratio (discussed in section 2.1.1.1). The degree of hydration (as a percentage) can be obtained by dividing the amount of chemically bound water (of Figure 9-1) by 0,23 grams of water per grams of cement*. The error introduced by approximating the degree of hydration with Figure 9-1 could be significant, and allows the subsequent theory to be only a demonstration of the variation of cement paste properties with depth from exposed surfaces.

- The empirical formula used to calculate pore relative humidity [Parrott, 1988] is only applicable for a constant temperature of 20°C. Thus the combined effect of temperature on evaporation and hydration rates cannot be included in this theory.
- This formula is also independent of the period of wet curing. This is understandable when considering that the minimum period of wet curing investigated was 3 days (for OPC concretes). In Chapter 7 it was shown that the differences in the durability indexes between concretes wet cured for 3, 7 and 28 days (for drying regimes 4, 5 and 6) were small, indicating similar pore structures of the cement paste. This explains why Parrott's results were insensitive to wet curing, and implies that 1 day of wet curing cannot be included in the subsequent discussion.

* The value of 0,23 g/g can be taken as a typical value for a degree of hydration of 100% [Soroka, 1979].

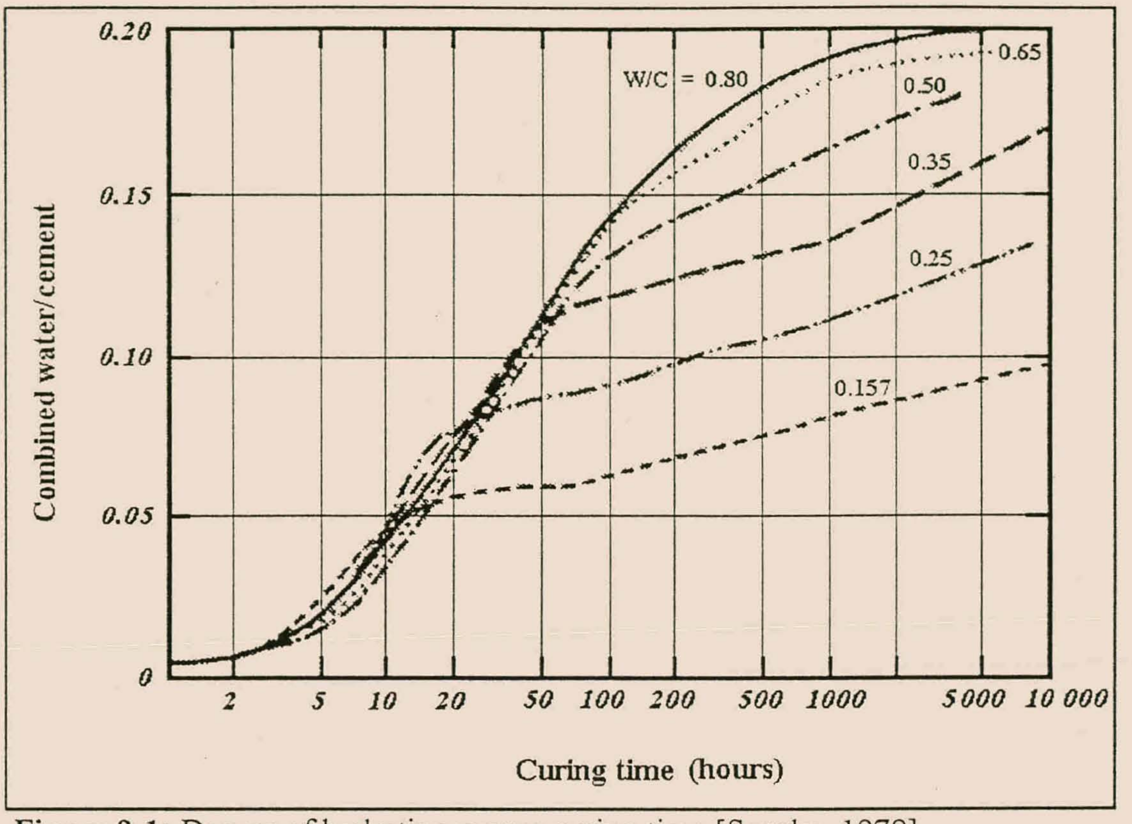

Figure 9-1: Degree of hydration versus curing time [Soroka, 1979]

9.2. Drying of well cured concretes, exposed to varying relative humidities and a temperature of 20°C

9.2.1. Calculation of additional curing period

Work was done by Parrott [1988] during which an empirical equation was derived to calculate pore relative humidity, as a function of depth into the concrete, drying time, w:c ratio, ambient relative humidity and percentage binder replaced by fly ash or slag. This work was discussed in section 2.3.2.4, and the range of exposure conditions and w:c ratios correlated with the constant temperature environments of this investigation (fully wet cured results (environment 1) and drying regimes 4, 5 and 6).

Thus this equation can be used to calculate approximate pore relative humidities for the exposure conditions of 20°C and 54%, 66% and 82% ambient relative humidity, and OPC concretes with w:c ratios of 0,40, 0,56 and 0,84.

Parrott's equation is given by:

$$PRH = RH + (100 - RH)\left[\frac{1}{1 + \dfrac{t}{\dfrac{d_{ex}^{\ 1,35}(70 - e_f)(w - 0,19)}{8}}}\right] \tag{9-1}$$

where PRH = pore relative humidity (%)

RH = ambient relative humidity (%)

t = drying time after initial curing (days)

d_{ex} = depth into the concrete (mm)

e_f = percentage OPC replaced with ggbs or fly ash

w = water:binder ratio

The objective is to calculate the additional curing period at any depth into the concrete, in other words the period of time required for the pore relative humidity (at depth d_{ex}), to reduce to 95%.

By setting PRH = 95, e_f = 0 and solving for t, the equation reduces to:

$$t = -0,4375 d_{ex}^{\ 1,35}\left[\frac{100w - 19}{RH - 95}\right] \tag{9-2}$$

for $RH < 95$

where t is now equal to the additional curing period (in days) at any concrete depth (t_a).

9.2.2. Calculation of degree of hydration

With the initial curing (t_{in}) period known, and t_a calculated from equation 9-2, the effective curing period (t_e in days) at any depth into the concrete is equal to the sum of t_{in} + t_a. The degree of hydration can be obtained from Figure 9-1, or from the empirical equations in Table 9-1 (the derivation of these formulae were obtained from Figure 9-1, and is given in Appendix F).

Table 9-1: Formulae for calculating the effective degree of hydration, as a function of effective curing period and w:c ratio

Effective period of wet curing (t_e in days)	**Formula for effective degree of hydration (α_e)***
1	α_e = 35,01%
2	α_e = 47,14%
3	$\alpha_e = -0{,}1780w^2 + 0{,}3405w + 0{,}4007$
4	$\alpha_e = -0{,}4322w^2 + 0{,}7122w + 0{,}3136$
5 and above	$\alpha_e = (0{,}1376w - 0{,}015)\ln(t_e) + z$**

* These formulae are only applicable for w:c ratios ≥ 0,35

** z = 0,507 for w:c ratios ≥ 0,50

$z = 0{,}266w + 0{,}375$ for w:c ratios < 0,50 (9-3)

9.2.3. Calculation of the capillary porosity of the cement paste

The capillary porosity can be calculated from the following equation (taken from Soroka [1979] and discussed in section 2.1.2.1):

$$p_c = 1 - R_{c+g} \tag{9-4}$$

where p_c = capillary porosity of the cement paste (%)

R_{c+g} = the volume fraction of the gel plus unhydrated cement in the cement paste (%)

R_{c+g} is given by:

$$R_{c+g} = \frac{0,32 + 0,384\alpha_e}{0,32 + w} \tag{9-5}$$

9.3. Application of the calculated capillary porosity

The preceding theory provides a helpful tool in understanding the effect of drying on the capillary porosity of the cement paste. This property can now be calculated for the 3 and 7 day wet cured concretes of environments 4, 5 and 6, as well as for the fully wet cured results of this investigation. As an example, calculations are shown to estimate the capillary porosity of a concrete with a w:c ratio of 0,56, initial period of wet curing of 3 days and exposed to an ambient relative humidity of 66% (temperature = 20°C), at a depth of 10 mm.

9.3.1. Sample calculation

Given:

$w = 0,56$

$t_{in} = 3$ days

$RH = 66\%$

$d_{ex} = 10$ mm

Additional curing period (t_a):

The additional curing period is calculated from equation 8-2, i.e.

$$t_n = -0{,}4375 d_{ex}^{\ 1,35} \left[\frac{100w - 19}{RH - 95} \right]$$

t_a = 12,5 days

Effective curing period:

The effective curing period is equal to the sum of the initial and additional curing periods, i.e.

$t_e = t_{in} + t_a$

t_e = 15,5 days

Degree of hydration:

The degree of hydration is equal to:

$\alpha_e = (0{,}1376w\text{-}0{,}015)\ln(t_e) + z$

For a w:c ratio of 0,56, z = 0,507, thus

α_e = 67,71%

Capillary porosity:

The capillary porosity is equal to:

$$p_c = 1 - \frac{0,32 + 0,384\alpha_e}{0,32 + w}$$

$$p_c = 34,09\%$$

Figures 9-2 and 9-3 illustrate the variations of pore relative humidity, capillary porosity and degree of hydration with depth (for the above conditions). Note that the concrete region illustrated corresponds to that of a typical core retrieved for the durability index tests, i.e. a thickness of 25 mm, with the outer 5 mm discarded during preparation of the sample. Furthermore, the cores of this investigation were retrieved 28 days after *casting*, implying that the effective curing period (t_e) cannot be longer than 28 days (i.e. $t_e \leq 28$). Therefore the effective curing period at depths greater than 17,5 mm (in this particular case) is equal to 28 days, resulting in a constant capillary porosity for concrete depths ≥ 17,5 mm. For the fully cured concretes, the capillary porosity would theoretically be constant throughout the sample thickness.

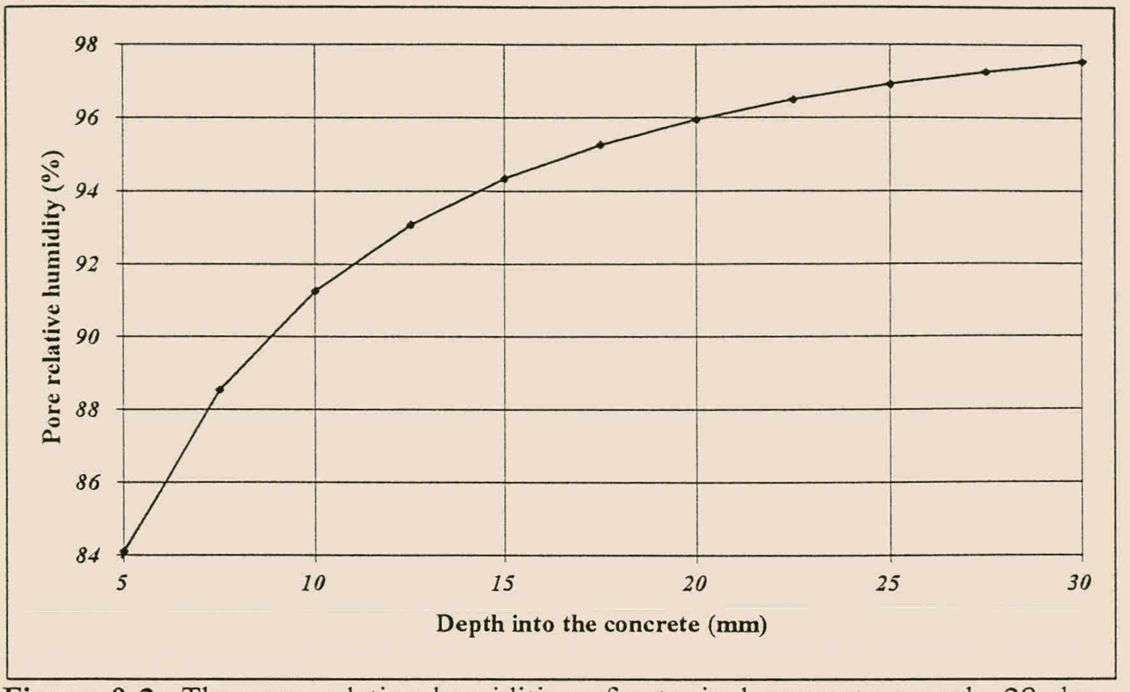

Figure 9-2: The pore relative humidities of a typical concrete sample 28 days after casting, with a w:c ratio of 0,56, initial period of wet curing of 3 days and drying at 66% ambient relative humidity (at 20°C) for 25 days (environment 5)

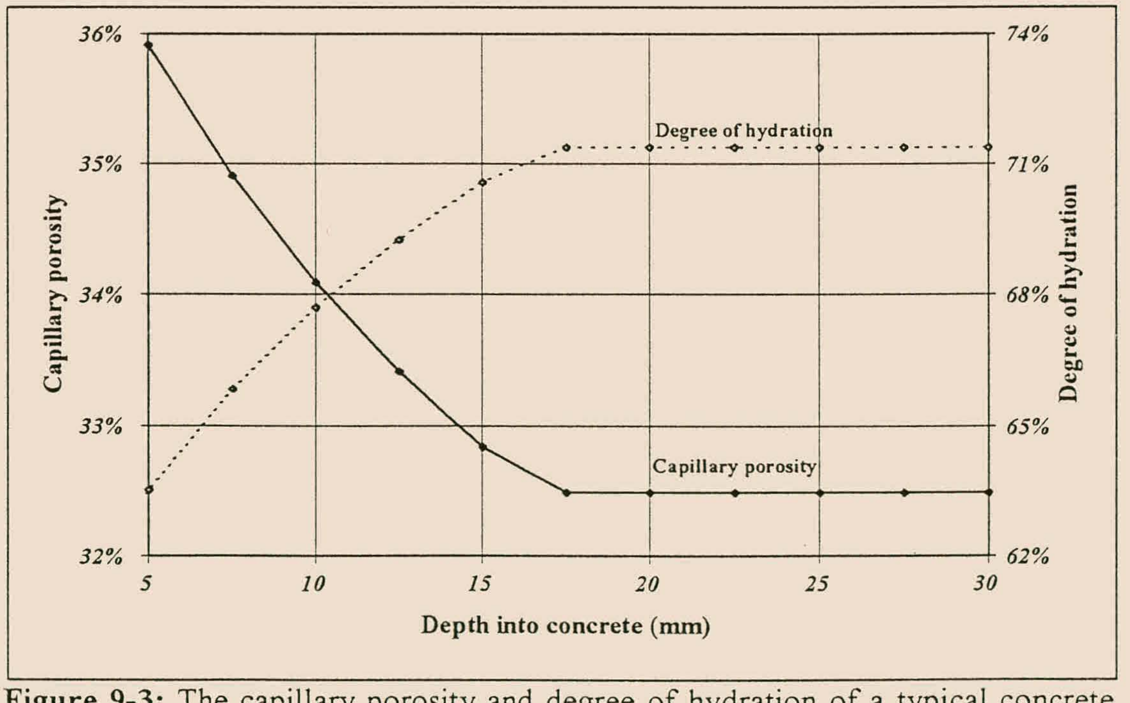

Figure 9-3: The capillary porosity and degree of hydration of a typical concrete sample 28 days after casting, with a w:c ratio of 0,56, initial period of wet curing of 3 days and drying at 66% ambient relative humidity (at 20°C) for 25 days (environment 5)

The above calculations can be repeated for the other two concrete grades (w:c ratios of 0,40 or 0,84), for ambient relative humidities of 54% or 82%, and for concretes with initial periods of wet curing of 3, 7 or 28 days. In other words, the capillary porosity characteristics of the concretes of environments 1, 4, 5 and 6 of this investigation (with the exception of the 1 day wet cured concretes) can be estimated with the above method.

9.3.2. Relationships between the capillary porosity and the results obtained from the durability index tests

The approximate results provided by the above theory can be used to relate the capillary porosity of the covercrete to the durability indexes obtained in the above environments. Because of the fact that the accuracy of the answers obtained is unknown, such relationships can only serve as an illustration of the type of trends that can be expected. In general, it seemed that there are definite relationships between the capillary porosity characteristics of the covercrete and the indexes obtained.

Chloride conductivity and oxygen permeability are functions of the concrete properties throughout the entire sample thickness, while the water sorptivity index indicates the penetration depth of absorbed water per square root of time. The expectation was thus that the first two indexes would be a function of the capillary porosity of the entire sample, while the latter index would be more sensitive to the capillary porosity of the outer region of the covercrete*.

Thus the chloride conductivity and oxygen permeability were related to the average capillary porosity of the cement paste, while the water sorptivity showed

* Water sorptivity indexes obtained were typically between 8 to 15 mm/√h, but could be as much as 25 mm/√h under severe conditions. This implies that, during a typical test of 64 minutes, the front of absorbed water penetrates the covercrete to depths ranging from 8 mm to 25 mm.

a better correlation with the volume of the capillaries** within the first 10 mm*** into the concrete.

9.3.2.1. *Calibration of results*

Due to the differences in the fully cured results obtained from the different drying regimes, the indexes obtained had to be normalised if they were to be related to the calculated capillary porosity of the cement paste. This was done by multiplying the relative indexes (used in the previous chapter for assessing the influences of relative humidity and temperature) by the average fully cured result of all the environments (see Table 7-1). Furthermore, the smoothed (or adjusted) index values were used (see section 7.1), in order to relate the calculated capillary porosity to the general trends observed from the experimental results.

9.3.2.2. *Chloride conductivity*

The normalised chloride conductivity indexes (defined as above) were plotted against the average capillary porosity of the samples (Figure 9-4). The latter was calculated by integration of the capillary porosity with depth, and dividing the result by the thickness of the sample (25 mm).

The second order polynomial trend line proved to be a good fit for the data. The y-intercept was set to zero, implying no chloride conductivity for samples containing no capillary pores. This is not strictly true, since chloride ions are smaller than gel pores, and thus the chloride conductivity of cement gel will not necessarily be zero.

** Due to the varying aggregate content of the three concrete grades, the volume of cement paste increased with decreases in w:c ratio. Therefore, the volume of capillaries varied for constant capillary porosity, but different w:c ratios.

*** Using the depth of penetration of absorbed water significantly complicated calculations. Thus 10 mm was selected, since the porosity characteristics within this region was expected to influence any water sorptivity result.

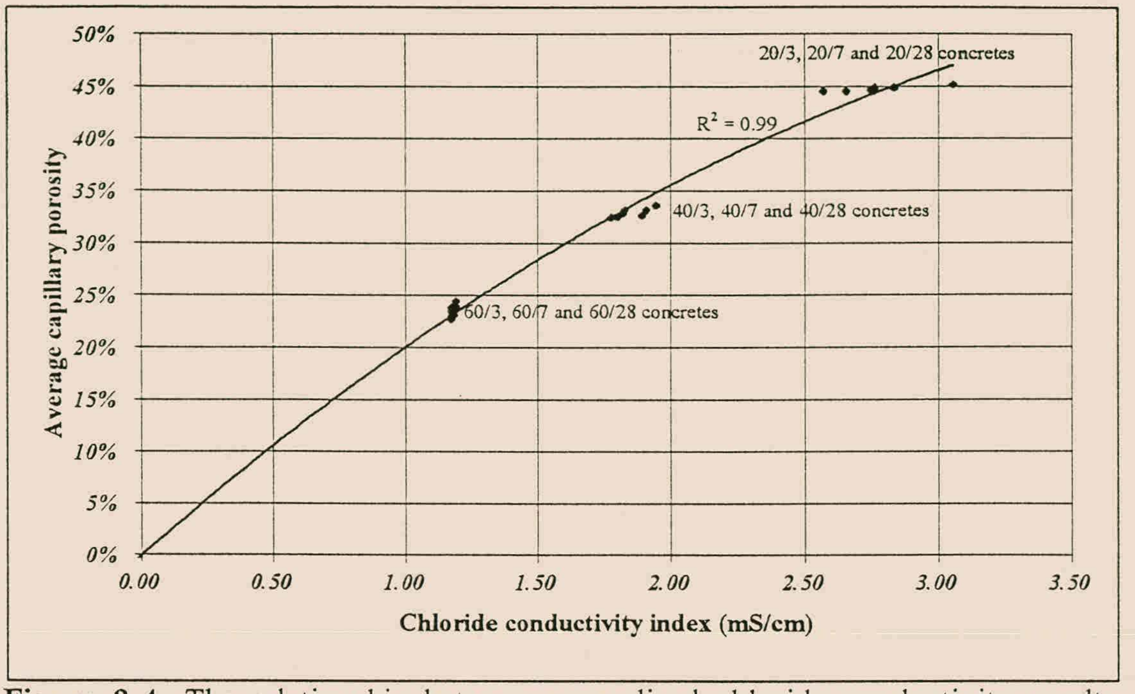

Figure 9-4: The relationship between normalised chloride conductivity results (from environments 1, 4, 5 and 6) and the calculated average capillary porosity of the cement paste (9-4)

However, the chloride conductivity of cement gel, in the absence of any capillary pores, should be very small in comparison to the results of this investigation, and the error introduced by setting the y-intercept to zero can be regarded as negligible for the purposes of this discussion.

9.3.2.3. Oxygen permeability

The normalised oxygen permeability indexes were plotted against the average capillary porosity of the samples (Figure 9-5). The second order polynomial trend line proved to be a good fit for the data, but cannot be extrapolated to oxygen permeabilities lower than 9,2, which was the overall poorest result observed in the constant temperature drying regimes.

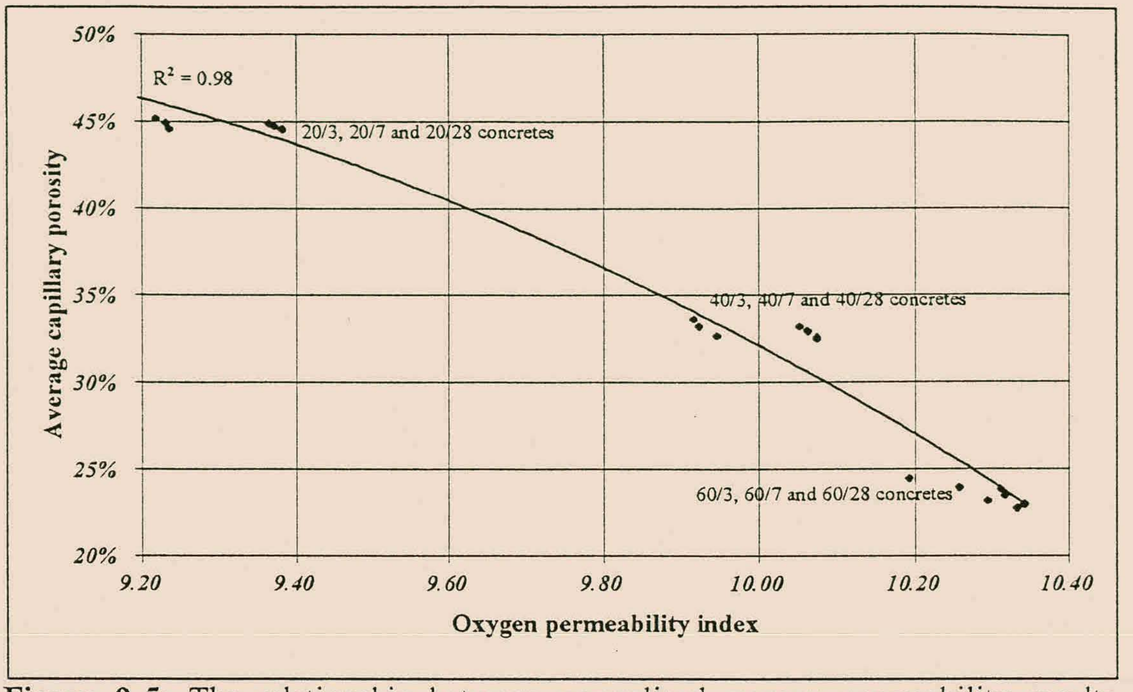

Figure 9-5: The relationship between normalised oxygen permeability results (from environments 1, 4, 5 and 6) and the calculated average capillary porosity of the cement paste (9-5)

9.3.2.4. Water sorptivity

The normalised water sorptivity indexes were plotted against the capillary volume of the cement paste in the outer 10 mm of the concrete samples (Figure 9-6). The second order polynomial trend line proved to be a good fit for the data. The y-intercept was set to zero, implying that samples containing no capillary pores would not absorb any water. This is a reasonable assumption, since the absorption of water is a function of capillary action and presumably relatively insensitive to gel porosity.

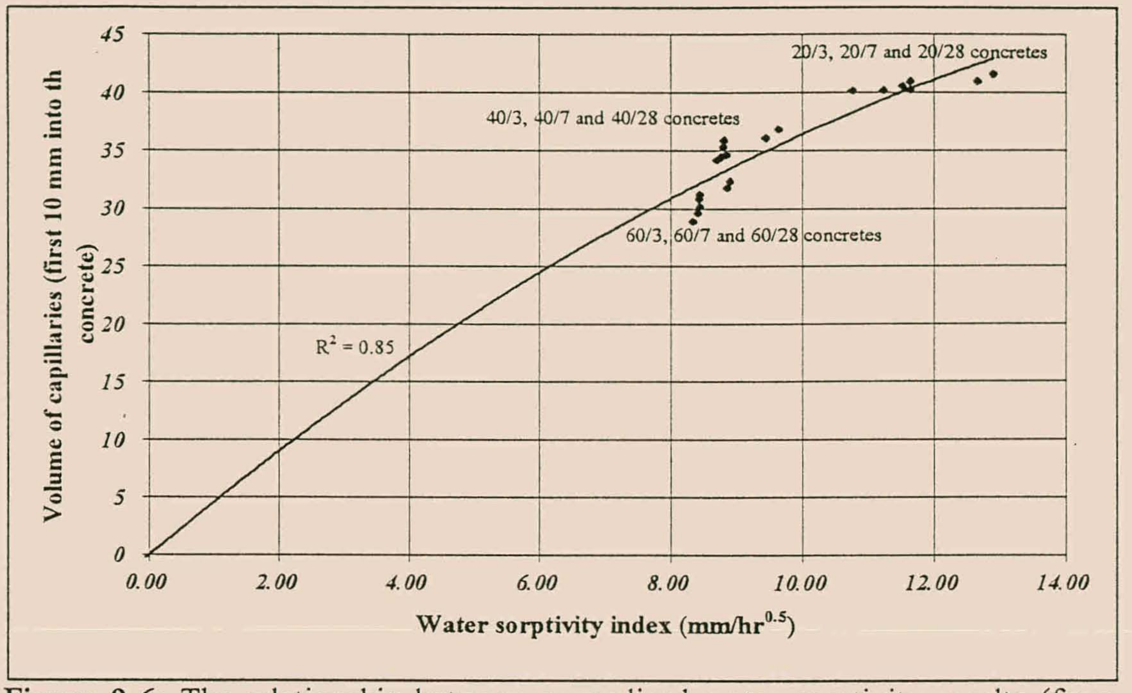

Figure 9-6: The relationship between normalised water sorptivity results (from environments 1, 4, 5 and 6) and the calculated capillary volume of the cement paste in the outer 10 mm of the concrete samples (9-6)

9.4. The effects of temperature and initial curing period on the drying of concrete

The next step will be to include the combined effects of temperature on the rates of evaporation and hydration in the drying model. The only method to obtain sufficient data, is by further research during which pore relative humidities, degree of hydration and porosity variations are monitored. The Parrott equation (equation 9-1), will have to be adjusted to accommodate varying temperatures. Furthermore, the effective degree of hydration (equations 9-3) can possibly be better approximated with a computer simulation, which is sensitive to the cement composition and fineness, as well as curing temperature.

The influence of the initial curing period proved to be significant in this investigation, but its influence on the retention of moisture, and the subsequent development of cement paste properties, is unknown. The only method to determine the influence of wet curing, would be by extensive measurements of these properties under varying drying conditions.

9.5. Conclusions

The rate of moisture changes in hardened concrete is influenced by the severity of the environment and the ability of the concrete to retain its moisture. More severe exposure conditions cause more rapid evaporation, while denser pore structures resist the evaporation and transport of moisture to exposed surfaces.

The extended availability of sufficient moisture at deeper concrete regions results in continued hydration and alteration of cement paste properties. These processes are also functions of temperature, and are accelerated by higher temperatures.

The influence of drying processes can be regarded in terms of decreases in pore relative humidity and the resulting development of the porosity characteristics of the cement paste. The effective degree of hydration was defined as hydration significantly affecting the porosity characteristics of the cement paste, i.e. hydration at pore relative humidities higher than 95%. The model attempts to relate the calculated capillary porosity characteristics of the covercrete to the durability indexes obtained during this investigation.

The model can be divided into the following steps:

- Calculation of an effective curing period, during which the pore relative humidity, at any depth, reduces to 95%.
- Calculation of the effective degree of hydration.
- Calculation of capillary porosity.
- Relation of the capillary porosity characteristics to the durability indexes obtained during this investigation.

9.5.1. Limitations

The theory formulated has the following limitations:

- The accuracy of the empirical formulae to calculate degree of hydration is unknown.
- The empirical formula used to calculate pore relative humidity [Parrott, 1988] is only applicable for a constant temperature of 20°C, and is independent of period of wet curing. Thus the combined effect of temperature on evaporation and hydration rates, as well as the influence of poor curing conditions, was not included in this theory.

9.5.2. Relationships between the capillary porosity and the results obtained from the durability index tests

The chloride conductivity and oxygen permeability indexes obtained in the constant temperature regimes, were related to the average (calculated) capillary porosity of the covercrete. The water sorptivity was related to the capillary volume in the outer 10 mm of the test samples.

The trends observed appear to indicate that there are good relationships between the durability indexes and the capillary porosity characteristics of the cement paste. Further research in this field could pursue this issue, by combining the durability index tests with measurements of pore relative humidities, degree of hydration and the porosity characteristics of the covercrete.

10. CONCLUSIONS AND RECOMMENDATIONS

The primary objective of this investigation was to determine and rate the influences of temperature, relative humidity and wind speed on the potential durability of OPC concretes. Three concrete grades were investigated, which were 20, 40 and 60 MPa. These concretes were wet cured for periods of 1, 3 and 7 days before the start of exposure, to determine the importance of wet curing as a function of the different environmental conditions.

The temperature investigations were done at a relative humidity of approximately 50%, and the relative humidity investigations at a temperature of approximately 20°C. Temperatures investigated were 20, 28 and 35°C, and relative humidities investigated were 54%, 66% and 82%. The investigation of wind speed was limited to 5,6 m/s.

During the drying period, which lasted until 28 days after casting, the moisture losses from the concrete samples were monitored. At the end of the drying periods, the samples were subjected to the durability index tests. The moisture losses from the samples and the durability index results showed the same trends, and provided sufficient data to interpret the influences of environmental conditions on the development of covercrete properties.

A theory was formulated for the drying processes of hardened concrete, which can be used to calculate the porosity characteristics of the covercrete, when exposed to varying relative humidities and a constant temperature of 20°C. This theory could be related to the durability indexes obtained from the drying regimes of varying relative humidity and constant temperature.

10.1. The influence of environmental conditions on results obtained

The three environmental factors investigated are discussed in order of significance on the results obtained, i.e. first temperature, then relative humidity and finally wind speed.

10.1.1. Temperature

Temperature had a large influence on the durability index results. In the case of poor quality concretes, elevated temperatures significantly reduced the quality of the covercrete. On the other hand, concretes with lower w:c ratios and proper initial curing seemed to benefit from the higher temperatures. This was due to the combined effect of temperature on the rates of hydration and evaporation.

The temperature which provided consistently good results, for all the concretes investigated, was 28°C. The implication is that the influence of this temperature on hydration rate outweighs increased rates of evaporation. The indexes obtained at 28°C seemed to indicate that this temperature generally provides good conditions for concreting.

10.1.2. Relative humidity

Relative humidities below 80% did not significantly influence the moisture losses or the durability indexes obtained. However, at 82% relative humidity, moisture losses decreased and the durability indexes improved markedly, for concretes of all grades and periods of wet curing.

10.1.3. Wind speed

Wind speed did not significantly influence the drying processes of hardened concrete, or the development of its pore structure. Possibly the best explanation for this is that wind cannot 'penetrate' the concrete surface, like temperature and relative humidity. Moisture can only evaporate at faster rates for as long as the drying front is situated within a concrete region with continuous capillary pores.

10.2. The importance of wet curing

The general observation that can be made from the results of this investigation is that 1 day of wet curing is not sufficient, as far as potential concrete durability is concerned. Thus 3 days of wet curing was essential for providing the covercrete with an adequate pore structure, to retain its moisture during initial drying processes.

10.2.1. Temperature variations

The lower concrete grades were very sensitive to temperature differences. At high temperatures (35°C), lack of wet curing resulted in large decreases in potential durability, while extended curing periods resulted in indexes close to, or even better than fully cured concretes (at 20°C). As a result of this, wet curing of at least 3 days was essential for all three concrete grades, when exposed to 35°C.

10.2.2. Relative humidity variations

Wet curing for 3 days was important at ambient relative humidities less than 80%. At 82% RH, almost all of the results obtained were similar to the fully cured results, implying that wet curing becomes negligible under such humid conditions.

10.2.3. Wind speed variations

The influence of wind speed was too insignificant to justify long periods of wet curing under windy conditions.

10.3. Summary of a model for the drying of hardened concrete

The influence of drying processes was regarded in terms of decreases in pore relative humidity and the resulting development of the porosity characteristics of the cement paste. The effective degree of hydration was defined as hydration significantly affecting the porosity characteristics of the cement paste, i.e. hydration at pore relative humidities higher than 95% [Patel et al, 1988].

The model can be divided into the following steps:

- Calculation of an effective curing period, during which the pore relative humidity, at any depth, reduces to 95%.
- Calculation of the effective degree of hydration.
- Calculation of capillary porosity.
- Relation of the capillary porosity characteristics to the durability indexes obtained during this investigation.

10.3.1. Limitations of the model

The theory formulated has the following limitations:

- The accuracy of the empirical formulae to calculate degree of hydration is unknown.
- The empirical formula used to calculate pore relative humidity [Parrott, 1988a] is only applicable for a constant temperature of 20°C, and is independent of period of wet curing. Thus the combined effect of temperature on evaporation and hydration rates, as well as the influence of poor curing conditions, was not included in this theory.

10.3.2. Relationships between the capillary porosity and the results obtained from the durability index tests

The chloride conductivity and oxygen permeability indexes obtained in the constant temperature regimes, were related to the average (calculated) capillary porosity of the covercrete. The water sorptivity was related to the capillary volume in the outer 10 mm of the test samples.

The trends observed appear to indicate that there are good relationships between the durability indexes and the capillary porosity characteristics of the cement paste.

10.4. Recommendations

In further research, the following aspects can be pursued for a better understanding of the problem:

- A wider scope of environmental conditions can be investigated. The trends observed during this investigation gives no indication of, for example, hot and dry conditions. Thus the significance of relative humidity and temperature may vary under different environmental conditions.
- Other cement types and cement extenders, like fly ash, slag and silica fume, can be included in future investigations.
- Structural elements other than slabs can be included.
- The sensitivity of the potential durability of high strength concretes could be investigated.
- It is strongly recommended that future research should combine the durability index tests with measurements of pore relative humidities, degree of hydration and the porosity characteristics of the covercrete.

REFERENCES

Abrams, M.S. and Orals, D.L. (1965) *Concrete Drying Methods and their Effect on Fire Resistance*, Portland Cement Association, Skokie, Publication No. RX181, 32 pp.

Addis, B.J. (Ed.) (1994) *Fulton's Concrete Technology*, Portland Cement Instituite, Midrand, South Africa. 7th edition, pp. 34-35.

ACI 305R-96 (1996) *Hot Weather Concreting*, Manual of Concrete Practice, Prt 2, Farmington Hills, American Concrete Institute, pp. 308.3.

Alexander, M.G. (1997) *An indexing approach to achieving durability in concrete structures*, FIP '97 Symposium: The Concrete Way to Development, Johannesburg, March 1997, Concrete Society of Southern Africa, pp. 571-576.

Alexander, M.G. and Magee, B.J. (1999) *Durability Performance of Concrete Containing Condensed Silica Fume*, Accepted for Publication in Cement and Concrete Research.

Bakker, R.F.M. (1983) *Permeability of Blended Cement Concretes*, V.M. Malhotra Ed., American Concrete Institute, Detroit, MI, SP-79, Vol. 2, pp. 589-605.

Ballim, Y. (1993) *Curing and the Durability of OPC, Fly Ash and Blast Furnace Slag Concretes*, Materials and Structures, Vol. 26, pp. 238-244.

Ballim, Y. (1991) *Concrete Curing. Description, Method and Control*, Concrete Societyof Southern Africa, pp. 4-7.

Bazant, Z.P. and Najjar, L.U. (1971) *Drying of Concrete as a Non-linear Diffusion Problem*, Cement and Concrete Research, Vol. 1, pp. 461-473.

Bouwer, S.M. (1998) *Practical Implimentation of Index Tests for Assessment and Control of Potential Concrete Durability*, M.Ing. Thesis, University of Stellenbosch.

Carrier, R.E. and Cady, P.D. (1970) *Evaluating Effectiveness of Concrete Curing Compound*, Journal of Materials, Vol. 5, No. 2, pp. 294-302.

Cather, B. (1994) *Curing: The True Story*, Guest Editorial Comment, Magazine of Concrete Research, Vol. 46, No. 168, pp. 157-161.

Copeland, L.E., Kantro, D.L. and Verbeck, G.J. (1960) *Chemistry of Hydration of Portland Cement,* Proceedings of Symposium on Chemistry of Cement, Washington, Vol. 1, pp. 429-468.

Fagerlund, G. (1982) *On the Capillarity of Concrete,* Nordic concrete research, Oslo, Publication No. 1, pp. 6.1- 6.20.

Glanville, J. and Neville, A. (1995) *Prediction of Concrete Durability,* Proceedings of Stats 21st Anniversary Conference, London, UK, pp. 18.

Grube, H. and Lawrence, C.D. (1984) *Permeability of Concrete to Oxygen,* Proceedings of the RILEM Seminar on Concrete Durability of Concrete Structures under Normal Outdoor Exposure, Hannover, RILEM, Paris, pp. 68-79.

Hearn, N., Hooton, R.D. and Mills, R.D. (1994) *Tests and Properties of Concrete: Pore Structure and Permeability,* Department of Civil Engineering, University of Toronto, Canada, pp. 240-262.

Ho, D.W.S., Cui, Q.Y. and Ritchie, D.J. (1989) *The Influence of Humidity and Curing Time on the Quality of Concrete,* Cement and Concrete Research, Vol. 19, pp. 457-464.

Kreijer, P.C. (1984) *The Skin of Concrete - Composition and Properties,* Matériaux et Constructions, Vol. 17, No. 100, pp. 275.

Lawrence, C.D. (1981) *Durability of Concrete: Molecular Transport Processes and Test Methods,* C & CA Technical Report 544, 25 pp.

Lawrence, C.D. (1985) *Transport of Oxygen through Concrete,* British Ceramic Proceedings, No. 35, Chemistry and chemically related properties of cement, pp. 277-293.

Mantel, D.G. (1992) *The Manufacture, Properties and Applications of Portland Cements, Cement Additives and Blended Cements,* Pretoria Portland Cement, pp. 15-16.

Midgley, H. and Illston, J.M. (1984) *The Penetration of Chlorides into Hardened Cement Paste,* Cement and Concrete Research, No. 41, pp. 546-558.

Mills, R.H. (1985) *Mass Transfer of Water Vapour Through Concrete,* Cement and Concrete Research, Vol. 15, pp. 74-82.

Mindess, S. and Young, J.F. (1988) *Concrete,* Prentice-Hall Inc., New Jersey.

O'Brien, F.E.M. (1948) *The Control of Humidity by Saturated Salt Solutions.* British Electrical and Allied Industries Research Association, London. Vol. 25, pp. 73-76.

Oberholster, R.E. (1986) 8th International Congress on the Chemistry of Cement, Rio de Janeiro, Brazil, Special Reports, Vol. 1.

Parrott, L.J. (1981) *Effect of Drying History upon the Exchange of Pore Water with Methanol and Subsequent Methanol Sorption Behaviour in Hydrated Alite Paste,* Cement and Concrete Research, Vol. 11, pp. 651-658.

Parrott, L.J., Killoh, D.C. and Patel, R.G. (1986) *Cement Hydration under Partially Saturated Conditions,* Proceedings of the 8th Congress on the Chemistry of Cement, Rio de Janeiro, Vol. 3, pp. 46-50.

Parrott, L.J. (1991) *Rate of Weight Loss during Initial Exposure as an Indicator of Cover Concrete Performance,* Report C/9, British Cement Association, 20 pp.

Parrott L.J. (1988a) *Moisture Profiles in Drying Concrete,* Advances in Cement Research, Vol. 1, No. 3, pp. 164-170.

Patel R.G. et al. (1988) *Influence of Curing at Different Relative Humidities upon Compound Reactions and Porosity in Portland Cement Paste,* Materials and Structures, Vol. 21, pp. 192-197.

Powers, T.C. (1947) *A Discussion of Cement Hydration in Relation to the Curing of Concrete,* Portland Cement Association, Skokie, Publication No. RX25, 12 pp.

Powers, T.C. (1954) *Permeability of Portland Cement Pastes,* Journal, American Concrete Institute, Vol. 51, pp. 285-298.

Powers, T.C. (1958) *Structure and Physical Properties of Hardened Portland Cement Paste,* Journal, American Ceramic Society, Vol. 41, pp. 1-6.

Powers, T.C. (1960) *Physical Properties of Cement Paste,* Proceedings of the 4th International Symposium on the Chemistry of Cement, Washington DC, Vol. 2, pp. 577-613.

Powers, T.C. (1978) *The Nature of Concrete,* ASTM STP 169B: Significance of Tests and Properties of Concrete and Concrete-Making Materials, pp. 59-73.

Powers, T.C. and Brownyard, T.L (1946). *Studies of the Physical Properties of Hardened Portland Cement Paste,* J American Concrete Institute, Vol. 18, No. 2-8.

Rose, D.A. (1965) *Water Movement in Unsaturated Porous Materials,* Materials and Structures, RILEM, Paris, Bulletin No. 29, pp. 119-123.

SABS 0100-1 & 2 (1992) *Code of Practice for the Structural Use of Concrete. Part I: Design; Part 2: Materials and Execution of Work,* Pretoria: South African Bureau of Standards.

SABS 1083-1976 (1976) *Specification for Aggregates from Natural Resources,* Pretoria: South African Bureau of Standards.

SABS Method 829:1976 (1976) *Fines Content, Dust Content and Sieve Analysis of Aggregates,* Pretoria: South African Bureau of Standards.

Soroka, I. (1979) *Portland Cement Paste and Concrete,* MacMillan Press Ltd., London and Basingstoke, pp. 4, 30-36, 39-41, 51-52, 60-62, 87-88,115-116.

Soroka, I. (1979) *Portland Cement Paste and Concrete,* MacMillan Press Ltd., London and Basingstoke, pp. 115-116.

Spears, R.E. (1983) *The 80% Solution to Inadequate Curing Problems,* Concrete International, ACI, April 1983, pp. 15-18.

Streicher, P.E. (1996) *Durability of Marine Cements,* PPC/UCT Research project, Final Project Report, University of Cape Town, Department of Civil Engineering, pp. 2.7.

Taplin, J.H. (1959a) *A Method for Following the Hydration Reaction in Portland Cement Paste,* Australian Junior Applied Science, Vol. 10, pp. 329-345.

Taplin, J.H. (1959b) *The Temperature Dependence of the Hydration Rate of Portland Cement Paste,* Australian Junior Applied Science, Vol. 13, No. 2, pp. 329-345.

Uno, P.J. (1998) *Plastic Shrinkage Cracking and Evaporation Formulas,* ACI Materials Journal, Vol. 95, No. 4, July-August 1998, pp. 365-375.

Verbeck, G. (1978) *Pore Structure,* ASTM STP 169B: Significance of Tests and Properties of Concrete and Concrete-Making Materials, pp. 262-274.

Xi, Y., Bazant Z.P. and Jennings, H.M. (1994) *Moisture Diffusion in Cementitious Materials*, Advanced Cement Based Materials, Vol. 1, pp. 248-257.

APPENDIX A - SIEVE ANALYSES

The sieve analyses of the Klipheuwel sand are given in Tables A-1 to A-3, while Table A-4 gives the average analysis of the three samples.

Table A-1: Sieve analysis of the first sample of Klipheuwel sand

Sieve aperture (mm)	Retained mass (g)	Percentage retained	Cumulative percentage retained	Cumulative percentage passing
4,750	0,0	0,0	0,00	100,0
2,360	5,0	0,5	0,53	99,5
1,180	50,0	5,3	5,82	94,2
0,600	335,0	35,4	41,27	58,7
0,300	220,0	23,3	64,55	35,4
0,150	175,0	18,5	83,07	16,9
0,075	120,0	12,7	95,77	4,2
< 0,075	40,0	4,2	100,00	0,0
Total	**945,0**	**100,0**		
Fineness Modulus			**1,95**	

Table A-2: Sieve analysis of the second sample of Klipheuwel sand

Sieve aperture (mm)	Retained mass (g)	Percentage retained	Cumulative percentage retained	Cumulative percentage passing
4,750	0,0	0,0	0,00	100,0
2,360	5,0	0,4	0,43	99,6
1,180	75,0	6,5	6,90	93,1
0,600	435,0	37,5	44,40	55,6
0,300	265,0	22,8	67,24	32,8
0,150	215,0	18,5	85,78	14,2
0,075	125,0	10,8	96,55	3,4
< 0,075	40,0	3,4	100,00	0,0
Total	1160,0	100,0		
Fineness Modulus			**2,05**	

Table A-3: Sieve analysis of the third sample of Klipheuwel sand

Sieve aperture (mm)	Retained mass (g)	Percentage retained	Cumulative percentage retained	Cumulative percentage passing
4,750	0,0	0,0	0,00	100,0
2,360	5,0	0,5	0,51	99,5
1,180	55,0	5,6	6,06	93,9
0,600	350,0	35,4	41,41	58,6
0,300	230,0	23,2	64,65	35,4
0,150	190,0	19,2	83,84	16,2
0,075	120,0	12,1	95,96	4,0
< 0,075	40,0	4,0	100,00	0,0
Total	990,0	100,0		
Fineness Modulus			**1,96**	

Table A-4: Average of the three sieve analyses

Sieve aperture (mm)	Retained mass (g)	Percentage retained	Cumulative percentage retained	Cumulative percentage passing
4,750	0,0	0,0	0,0	100,0
2,360	5,0	0,5	0,5	99,5
1,180	60,0	5,8	6,3	93,7
0,600	373,3	36,1	42,4	57,6
0,300	238,3	23,1	65,5	34,5
0,150	193,3	18,7	84,2	15,8
0,075	121,7	11,9	96,1	3,9
< 0,075	40,0	3,9	100,0	0,0
Total	1031,7			
Fineness Modulus			**1,99**	

APPENDIX B - COMPRESSIVE STRENGTH AND SLUMP MEASUREMENTS

The results of the compressive strength tests of drying regimes 2 to 6 are given in Tables B-1 to B-5, while the slumps of all fresh concrete batches are given in Table B-6.

Table B-1: Compressive strengths of samples from environment 2

Specimen marking	Age at test (days)	Mass	Dimensions (mm)	Density (kg/m^3)	Failure load (kN)	Compressive strength (MPa)	Average compressive strength (MPa)	Standard deviation (MPa)
20/2/1	28	2415	100	2415	200	20,0	19,3	0,6
20/2/2	28	2321	100	2321	189	18,9		
20/2/3	28	2428	100	2428	190	19,0		
40/2/1	28	2439	100	2439	398	39,8	39,7	1,1
40/2/2	28	2449	100	2449	386	38,6		
40/2/3	28	2421	100	2421	407	40,7		
60/2/1	28	2481	100	2481	580	58,0	58,3	1,3
60/2/2	28	2406	100	2406	571	57,1		
60/2/3	28	2494	100	2494	597	59,7		

Table B-2: Compressive strengths of samples from environment 3

Specimen marking	Age at test (days)	Mass	Dimensions (mm)	Density (kg/m^3)	Failure load (kN)	Compressive strength (MPa)	Average compressive strength (MPa)	Standard deviation (MPa)
20/3/1	28	2342	97,5	2527	170	17,9	18,8	0,8
20/3/2	28	2441	101,5	2334	199	19,3		
20/3/3	28	2416	101	2345	195	19,1		
40/3/1	28	2493	101	2420	400	39,2	39,0	0,2
40/3/2	28	2466	100,5	2429	393	38,9		
40/3/3	28	2469	100	2469	390	39,0		
60/3/1	28	2506	101	2432	575	56,4	56,2	0,2
60/3/2	28	2507	100,5	2470	568	56,2		
60/3/3	28	2508	100	2508	560	56,0		

Table B-3: Compressive strengths of samples from environment 4

Specimen marking	Age at test (days)	Mass	Dimensions (mm)	Density (kg/m^3)	Failure load (kN)	Compressive strength (MPa)	Average compressive strength (MPa)	Standard deviation (MPa)
20/4/1	28	2457	100	2457	170	17,0	18,8	1,6
20/4/2	28	2436	99,5	2473	199	20,1		
20/4/3	28	2435	100,5	2399	195	19,3		
40/4/1	28	2486	100	2486	400	40,0	39,4	0,5
40/4/2	28	2464	100,5	2427	393	38,9		
40/4/3	28	2448	99,5	2485	390	39,4		
60/4/1	28	2539	99,5	2577	575	58,1	56,4	1,5
60/4/2	28	2553	101	2478	568	55,7		
60/4/3	28	2560	100,5	2522	560	55,4		

Table B-4: Compressive strengths of samples from environment 5

Specimen marking	Age at test (days)	Mass	Dimensions (mm)	Density (kg/m^3)	Failure load (kN)	Compressive strength (MPa)	Average compressive strength (MPa)	Standard deviation (MPa)
20/5/1	28	2374	100,5	2339	140	13,9	14,0	0,2
20/5/2	28	2368	101	2298	145	14,2		
20/5/3	28	2390	100	2390	140	14,0		
40/5/1	28	2375	98,5	2485	365	37,6	37,1	2,1
40/5/2	28	2416	100,25	2398	350	34,8		
40/5/3	28	2394	100	2394	390	39,0		
60/5/1	28	2460	100	2460	585	58,5	58,3	1,3
60/5/2	28	2464	100	2464	595	59,5		
60/5/3	28	2529	100	2529	570	57,0		

Table B-5: Compressive strengths of samples from environment 6

Specimen marking	Age at test (days)	Mass	Dimensions (mm)	Density (kg/m^3)	Failure load (kN)	Compressive strength (MPa)	Average compressive strength (MPa)	Standard deviation (MPa)
20/6/1	28	2428	99	2502	210	21,4	20,6	0,7
20/6/2	28	2463	100	2463	200	20,0		
20/6/3	28	2441	100	2441	205	20,5		
40/6/1	28	2524	101	2450	391	38,3	39,2	1,1
40/6/2	28	2518	100	2518	405	40,5		
40/6/3	28	2501	100	2501	389	38,9		
60/6/1	28	2509	100	2509	590	59,0	56,8	2,2
60/6/2	28	2501	101	2427	580	56,9		
60/6/3	28	2507	100,5	2470	551	54,6		

Table B-6: Slumps measured for the concrete batches of environments 2 to 6

Concrete grade (MPa)	Slump measured in drying regime (mm): 2	3	4	5	6	Average slump
20	40	60	55	50	45	50
40	45	40	45	50	45	45
60	50	30	45	40	35	40

APPENDIX C - MEASUREMENTS OF ENVIRONMENTAL CONDITIONS

In Tables C-1 to C-5, the environmental conditions measured in drying regimes 2 to 6 are given. Also shown are the calculated daily averages, as discussed in Chapter 5. Note that the average temperature is given to the nearest 0,1°C and the average relative humidity to the nearest 0,5%. In Tables C-6 the conditions of the two wind speed investigations are given.

Table C-1: Environmental conditions of drying regime 2

Date	Time	Time from the start of exposure (days)	Temperature (°C)	Relative humidity (%)	Calculated daily average temp. (°C)	Calculated daily average RH (%)
12-Nov-97	12:30	0,00	35,2	50,4	35,7	51,5
12-Nov-97	12:35	0,00	34,8	24,2		
12-Nov-97	13:45	0,05	36,3	51,1		
12-Nov-97	15:03	0,11	35,5	53,1		
13-Nov-97	10:14	0,91	37,5	48,3	36,7	52,3
13-Nov-97	10:18	0,91	36,5	50,9		
13-Nov-97	12:22	0,99	37,6	48,3		
13-Nov-97	12:35	1,00	35,2	32,5		
13-Nov-97	15:17	1,12	36,2	54,5		
13-Nov-97	15:43	1,13	35,8	59,5		
14-Nov-97	9:44	1,88	36,2	46,8	36,5	49,3
14-Nov-97	10:30	1,92	37,4	44,6		
14-Nov-97	13:25	2,04	36	51,9		
14-Nov-97	13:40	2,05	35,3	32,8		
14-Nov-97	14:34	2,09	36,2	51,3		
15-Nov-97	13:05	3,02	35,5	48	35,4	47,9
15-Nov-97	13:25	3,04	34,1	24,8		
15-Nov-97	15:35	3,13	37,4	50,5		
16-Nov-97	13:10	4,03	36	43,8	35,4	47,9
16-Nov-97	13:35	4,05	32,6	30		
16-Nov-97	16:00	4,15	34,8	52		
17-Nov-97	11:24	4,95	35,4	43,6	34,9	43,0
17-Nov-97	14:31	5,08	34,1	31,7		

17-Nov-97	15:33	5,13	34,4	42,3		
18-Nov-97	10:07	5,90	34,2	47,7	33,7	47,0
18-Nov-97	13:33	6,04	34,6	45,2		
18-Nov-97	13:50	6,06	33,8	47,8		
18-Nov-97	14:30	6,08	33,5	38,6		
18-Nov-97	15:25	6,12	32,2	47,2		
19-Nov-97	11:01	6,94	34	51,9	35,2	50,9
19-Nov-97	13:41	7,05	36	48,7		
19-Nov-97	14:10	7,07	34,8	39,1		
19-Nov-97	14:45	7,09	36,5	48,1		
19-Nov-97	15:25	7,12	34,1	54,8		
20-Nov-97	10:12	7,90	31,2	55,6	34,9	52,0
20-Nov-97	14:15	8,07	36,3	51,6		
20-Nov-97	14:34	8,09	35,1	53,9		
20-Nov-97	15:03	8,11	36,2	33,8		
20-Nov-97	15:35	8,13	37	46,9		
21-Nov-97	10:30	8,92	34,1	56,9	34,9	52,7
21-Nov-97	12:20	8,99	38	47,1		
21-Nov-97	14:36	9,09	33,6	58,3		
21-Nov-97	15:10	9,11	37,5	39,6		
21-Nov-97	15:50	9,14	33,9	48,6		
22-Nov-97	13:40	10,05	34,1	53,4	35,3	50,5
22-Nov-97	14:08	10,07	37,4	48,3		
22-Nov-97	14:35	10,09	33,4	46		
22-Nov-97	15:35	10,13	34,5	49,8		
23-Nov-97	12:35	11,00	35,6	54,6	35,0	55,7
23-Nov-97	15:35	11,13	34,4	56,8		
24-Nov-97	15:02	12,11	34,2	56,7	33,3	59,0
24-Nov-97	15:06	12,11	32,3	61,2		
25-Nov-97	8:00	12,81	32,6	50,4	34,1	47,5
25-Nov-97	8:10	12,82	35	42,8		
25-Nov-97	10:00	12,90	32,5	52,4		
25-Nov-97	11:35	12,96	35,1	44,2		
25-Nov-97	14:55	13,10	34,2	48		
25-Nov-97	15:14	13,11	29,3	45		
25-Nov-97	15:47	13,14	35,2	47,1		
26-Nov-97	7:00	13,77	33,4	50,1	34,0	49,4
26-Nov-97	9:04	13,86	33,8	49,7		
26-Nov-97	10:45	13,93	32,8	53,5		
26-Nov-97	10:47	13,93	36,4	46,1		
26-Nov-97	14:10	14,07	34,7	48		
26-Nov-97	14:25	14,08	31,2	39,1		

APPENDIX C - MEASUREMENTS OF ENVIRONMENTAL CONDITIONS

26-Nov-97	15:10	14,11	33,1	48,7		
27-Nov-97	6:50	14,76	34,7	46,4	34,5	49,8
27-Nov-97	9:11	14,86	33,8	49,4		
27-Nov-97	9:15	14,86	33	53		
27-Nov-97	9:17	14,87	36,9	45,1		
27-Nov-97	9:26	14,87	33,1	53		
27-Nov-97	10:31	14,92	33,3	54,9		
27-Nov-97	10:33	14,92	34,5	51,9		
27-Nov-97	10:44	14,93	34,9	49,2		
27-Nov-97	10:46	14,93	37,5	42,6		
27-Nov-97	10:53	14,93	32,9	54		
27-Nov-97	10:56	14,93	34	50,8		
27-Nov-97	15:13	15,11	35,5	47,4		
28-Nov-97	11:35	15,96	33,7	53,2	35,2	50,2
28-Nov-97	11:38	15,96	37,8	44,7		
28-Nov-97	12:45	16,01	34,6	50,8		
28-Nov-97	15:04	16,11	34,5	52,1		
29-Nov-97	14:56	17,10	38	48,7	36,3	50,4
29-Nov-97	15:07	17,11	34,8	56,6		
30-Nov-97	14:58	18,10	36,1	53,8	36,1	53,8
1-Dec-97	11:12	18,95	36,4	50,6	36,2	52,1
1-Dec-97	11:24	18,95	34,6	58,1		
1-Dec-97	11:26	18,96	37,9	48,8		
1-Dec-97	12:35	19,00	37	49,1		
1-Dec-97	15:30	19,13	35,3	54,1		
2-Dec-97	11:35	19,96	33,1	56	34,9	51,1
2-Dec-97	12:00	19,98	36,5	48,6		
2-Dec-97	15:07	20,11	35,2	48,8		
3-Dec-97	10:44	20,93	33,4	55,4	34,8	51,5
3-Dec-97	10:46	20,93	36,9	46,5		
3-Dec-97	14:22	21,08	34,1	52,5		
4-Dec-97	11:51	21,97	33,7	56,2	35,5	51,8
4-Dec-97	11:54	21,97	37,3	47,3		
5-Dec-97	14:50	23,10	34,2	56,9	36,1	52,2
5-Dec-97	14:54	23,10	37,9	47,4		
6-Dec-97	11:38	23,96	34,1	47,8	36,0	52,2
6-Dec-97	11:41	23,97	37,8	56,5		
7-Dec-97	11:38	24,96	37,5	47,5	35,8	52,4
7-Dec-97	14:30	25,08	34	57,3		
8-Dec-97	11:00	25,94	34,2	62,5	35,9	54,5
8-Dec-97	11:05	25,94	37,3	53,4		
8-Dec-97	12:20	25,99	37,4	46,4		

8-Dec-97	12:31	26,00	34,5	55,5		
9-Dec-97	9:07	26,86	34	59,2	35,8	54,5
9-Dec-97	9:10	26,86	37,5	49,7		
10-Dec-97	15:34	28,13	34,2	61,1	35,3	56,0
10-Dec-97	15:36	28,13	36,3	50,9		
11-Dec-97	14:44	29,09	34,2	60,9	36,0	56,8
11-Dec-97	14:46	29,09	37,8	52,6		
				Average conditions :	**35,3**	**51,5**

Table C-2: Environmental conditions of drying regime 3

Date	Time	Time from the start of exposure (days)	Tempe-rature (°C)	Relative humidity (%)	Calculated daily average temp. (°C)	Calculated daily average RH (%)
3-Mar-98	12:45	0,00	27,8	53,4	27,8	53,4
4-Mar-98	12:32	0,99	28,5	56,9	28,2	55,2
4-Mar-98	12:50	1,00	28,4	50,9		
5-Mar-98	12:00	1,97	28,2	57,6	28,5	54,3
4-Mar-98	12:02	0,97	31	50,4		
5-Mar-98	12:30	1,99	24,3	58,9		
6-Mar-98	11:45	2,96	27,9	60,1	28,5	58,1
6-Mar-98	12:47	3,00	30,7	52,7		
6-Mar-98	13:30	3,03	23,9	61,2		
7-Mar-98	12:35	3,99	26,9	56,4	27,6	54,1
7-Mar-98	12:37	3,99	30,2	47,7		
7-Mar-98	13:30	4,03	23,2	45,6		
8-Mar-98	13:36	5,04	26,9	58,3	27,7	55,8
8-Mar-98	13:40	5,04	30,3	49,1		
8-Mar-98	14:20	5,07	24,1	43,3		
9-Mar-98	10:48	5,92	26,5	55,2	27,2	52,9
9-Mar-98	10:51	5,92	29,8	46,6		
9-Mar-98	11:30	5,95	23	62,5		
10-Mar-98	10:29	6,91	26,7	53,9	27,2	51,6
10-Mar-98	10:31	6,91	29	45,3		
10-Mar-98	11:00	6,93	23,5	59,4		
11-Mar-98	11:40	7,95	27,1	55,6	27,7	53,6
11-Mar-98	11:44	7,96	29,9	48		
11-Mar-98	12:30	7,99	23,3	54,4		
12-Mar-98	10:14	8,90	26,6	56,7	27,3	54,4
12-Mar-98	10:17	8,90	29,8	48		
12-Mar-98	11:00	8,93	22,5	62,3		

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13-Mar-98	11:30	9,95	26,9	55,2	27,7	52,9
13-Mar-98	11:33	9,95	30,4	46,6		
13-Mar-98	12:15	9,98	23,6	61,8		
14-Mar-98	13:13	11,02	26,9	56,4	27,6	54,3
14-Mar-98	13:16	11,02	30,1	48,6		
14-Mar-98	14:00	11,05	24	54,1		
15-Mar-98	12:25	11,99	27,5	55,1	28,1	53,1
15-Mar-98	12:28	11,99	30,4	47,5		
15-Mar-98	13:00	12,01	24,5	47,6		
16-Mar-98	10:02	12,89	27,1	55,8	27,7	53,4
16-Mar-98	10:05	12,89	29,8	46,8		
16-Mar-98	11:00	12,93	22,6	65,3		
17-Mar-98	13:26	14,03	26,9	56,9	27,5	54,4
17-Mar-98	13:30	14,03	29,4	47,7		
17-Mar-98	14:00	14,05	25,5	45,1		
18-Mar-98	13:55	15,05	27,4	48,8	27,9	46,7
18-Mar-98	13:58	15,05	29,7	41		
18-Mar-98	14:30	15,07	25,1	41,2		
19-Mar-98	12:28	15,99	27,3	52,1	28,0	50,1
19-Mar-98	12:28	15,99	30,3	44,8		
20-Mar-98	13:05	17,01	27,9	53,6	28,4	51,3
20-Mar-98	13:08	17,02	30,3	45		
21-Mar-98	11:15	17,94	27,1	54,4	27,7	51,9
21-Mar-98	11:18	17,94	29,8	45,1		
22-Mar-98	10:05	18,89	27,4	54,5	28,1	52,3
22-Mar-98	10:10	18,89	30,7	46,2		
23-Mar-98	16:20	20,15	27,3	55,1	27,9	52,8
23-Mar-98	16:24	20,15	30,1	46,4		
24-Mar-98	9:50	20,88	27,3	54,7	28,0	52,5
24-Mar-98	9:54	20,88	30,6	46,4		
25-Mar-98	11:10	21,93	27,5	52,3	28,2	50,1
25-Mar-98	11:14	21,94	30,7	44,2		
26-Mar-98	12:10	22,98	27,5	52,1	28,2	49,9
26-Mar-98	12:13	22,98	30,5	44		
27-Mar-98	11:15	23,94	27,4	52	28,1	49,9
27-Mar-98	11:18	23,94	30,4	44,1		
28-Mar-98	12:10	24,98	27,1	54,2	27,7	51,8
28-Mar-98	12:13	24,98	29,8	45,2		
29-Mar-98	11:05	25,93	27,4	52,5	28,0	50,5
29-Mar-98	11:08	25,93	30,3	45,1		
30-Mar-98	7:40	26,79	27,3	55,8	28,0	53,6
30-Mar-98	7:43	26,79	30,6	47,5		

31-Mar-98	7:50	27,80	26,5	55	27,3	52,6
31-Mar-98	7:54	27,80	29,9	46,1		
1-Apr-98	7:35	28,78	27,1	49,1	27,8	47,6
1-Apr-98	7:38	28,79	30,1	43,4		
				Average conditions :	27,9	52,5

Table C-3: Environmental conditions of drying regime 4

Date	Time	Time from the start of exposure (days)	Tempe-rature (°C)	Relative humidity (%)	Calculated daily average temp. (°C)	Calculated daily average RH (%)
15-Apr-98	14:45	0,00	18,6	62,1	18,6	62,1
15-Apr-98	15:15	0,02	19,5	56,3		
15-Apr-98	16:12	0,06	19,2	53,7		
16-Apr-98	10:02	0,80	18,7	56,6	19,0	55,2
16-Apr-98	12:45	0,92	18,8	57,2		
16-Apr-98	13:00	0,93	19,8	71		
16-Apr-98	13:55	0,97	19,4	59,7		
16-Apr-98	15:45	1,04	19,2	50,8		
17-Apr-98	9:05	1,76	18,7	54,8	19,0	54,1
17-Apr-98	12:20	1,90	18,9	55,2		
17-Apr-98	12:37	1,91	19	60,1		
18-Apr-98	12:00	2,89	19,1	62,2	19,0	60,4
18-Apr-98	13:05	2,93	18,8	54,1		
18-Apr-98	15:05	3,01	19,6	51,5		
18-Apr-98	16:30	3,07	20,3	51,4		
19-Apr-98	9:30	3,78	20,7	50,6	20,3	51,6
19-Apr-98	9:55	3,80	20,5	58,4		
19-Apr-98	11:45	3,88	20,1	51,9		
20-Apr-98	7:40	4,70	18,9	46,7	19,6	49,9
20-Apr-98	9:00	4,76	18,8	47,7		
20-Apr-98	9:30	4,78	18,8	59,9		
20-Apr-98	10:35	4,83	18,7	46,8		
20-Apr-98	11:35	4,87	18,6	48		
20-Apr-98	13:20	4,94	18,7	47,1		
21-Apr-98	8:00	5,72	18,7	46	18,7	47,1
21-Apr-98	11:30	5,86	18,8	55,8		
21-Apr-98	12:30	5,91	19,1	60,1		
21-Apr-98	14:35	5,99	18,9	55,2		
22-Apr-98	7:30	6,70	19	53,1	18,9	54,1
22-Apr-98	8:30	6,74	19,1	54,7		

22-Apr-98	14:50	7,00	19,1	57,2		
23-Apr-98	11:00	7,84	19	53,5	19,1	55,4
23-Apr-98	11:30	7,86	19	61,6		
23-Apr-98	12:40	7,91	18,8	52,7		
24-Apr-98	13:14	8,94	19	51,2	18,9	52,3
24-Apr-98	13:30	8,95	18,9	53,2		
24-Apr-98	14:00	8,97	18,8	59,8		
24-Apr-98	15:00	9,01	18,9	53,3		
25-Apr-98	11:10	9,85	20	49,7	19,4	51,9
25-Apr-98	11:25	9,86	20,7	57,2		
26-Apr-98	12:55	10,92	20,9	58,4	20,8	57,8
26-Apr-98	14:15	10,98	20,9	46,5		
27-Apr-98	8:45	11,75	20,3	60,7	20,6	53,5
27-Apr-98	10:21	11,82	20,4	50,5		
27-Apr-98	11:30	11,86	20,3	45,6		
27-Apr-98	13:10	11,93	20,4	53,2		
27-Apr-98	14:00	11,97	20,5	51,4		
28-Apr-98	8:45	12,75	20,7	62,1	20,5	55,6
28-Apr-98	9:30	12,78	20,4	52,4		
28-Apr-98	13:50	12,96	19,2	44,8		
28-Apr-98	14:20	12,98	19,1	52,5		
29-Apr-98	8:10	13,73	18,3	44,3	19,0	48,7
29-Apr-98	8:20	13,73	18,4	53,2		
29-Apr-98	16:15	14,06	19,3	55,6		
29-Apr-98	17:25	14,11	18,9	50,5		
30-Apr-98	7:25	14,69	18,6	48	18,8	51,2
30-Apr-98	8:10	14,73	18,6	53		
30-Apr-98	9:00	14,76	18,7	61,2		
30-Apr-98	12:10	14,89	18,7	46,2		
1-May-98	10:20	15,82	20,3	57,8	19,4	52,3
1-May-98	11:20	15,86	19,4	48,2		
1-May-98	14:45	16,00	18,9	46		
1-May-98	15:35	16,03	19,4	46,4		
2-May-98	13:00	16,93	19,3	59,4	19,3	52,0
2-May-98	15:50	17,05	19,2	50,5		
3-May-98	10:50	17,84	19,1	57,6	19,2	54,2
4-May-98	9:45	18,79	17,9	65,7	18,5	61,7
4-May-98	10:00	18,80	17,9	55,6		
4-May-98	13:20	18,94	17,2	54		
4-May-98	15:45	19,04	17,2	54,9		
5-May-98	9:50	19,80	18,1	53,8	17,6	54,5
5-May-98	14:15	19,98	17,2	57,1		

6-May-98	9:50	20,80	17,4	55,2	17,4	56,0
7-May-98	11:30	21,86	17,4	56,7	17,4	56,0
7-May-98	13:20	21,94	17,6	56,2		
8-May-98	13:55	22,97	17,4	57,2	17,5	56,7
9-May-98	13:15	23,94	17,4	52,9	17,4	55,1
10-May-98	13:30	24,95	17,3	52,6	17,4	52,8
11-May-98	13:30	25,95	17,8	48	17,6	50,3
12-May-98	13:30	26,95	18,5	54,1	18,2	51,1
13-May-98	13:30	27,95	18	57	18,3	55,6
14-May-98	13:30	28,95	17,5	59	17,8	58,0
Average conditions :					**18,8**	**54,0**

Table C-4: Environmental conditions of drying regime 5

Date	Time	Time from the start of exposure (days)	Tempe-rature (°C)	Relative humidity (%)	Calculated daily average temp. (°C)	Calculated daily average RH (%)
6-May-98	13:55	0,00	17,4	59,6	18,5	63,4
6-May-98	14:30	0,02	17,5	73		
6-May-98	14:35	0,03	17,3	58		
6-May-98	15:20	0,06	17,4	62		
6-May-98	16:45	0,12	17,4	63,5		
6-May-98	17:15	0,14	17,4	64,4		
7-May-98	11:30	0,90	17,4	65,8	17,4	64,8
7-May-98	13:23	0,98	17,7	57,7		
7-May-98	13:44	0,99	17,6	65,2		
7-May-98	14:25	1,02	17,5	68,9		
7-May-98	14:30	1,02	17,5	57,1		
7-May-98	15:13	1,05	17,4	63,8		
7-May-98	15:45	1,08	17,4	64,1		
8-May-98	13:05	1,97	17,3	60,5	17,4	62,4
8-May-98	13:55	2,00	17,4	60,6		
8-May-98	15:00	2,05	17,4	70,3		
8-May-98	15:10	2,05	17,9	58,4		
8-May-98	15:47	2,08	17,6	69		
8-May-98	15:49	2,08	17,6	58,1		
8-May-98	16:50	2,12	17,6	63,1		
9-May-98	13:00	2,96	17,4	62,3	17,5	62,7
9-May-98	13:18	2,97	17,4	54		
9-May-98	14:18	3,02	17,4	65,7		
9-May-98	14:19	3,02	17,4	55,2		
9-May-98	15:10	3,05	17,3	64,7		

APPENDIX C - MEASUREMENTS OF ENVIRONMENTAL CONDITIONS

9-May-98	15:50	3,08	17,3	64		
10-May-98	13:15	3,97	17,4	58,2	17,4	61,1
10-May-98	13:40	3,99	17,2	54,3		
10-May-98	14:25	4,02	17,3	65,3		
10-May-98	15:35	4,07	17,3	65,3		
11-May-98	11:05	4,88	17,7	58,4	17,5	61,9
11-May-98	11:21	4,89	17,5	49,4		
11-May-98	13:10	4,97	18,6	59,4		
11-May-98	16:10	5,09	20	61,4		
11-May-98	16:50	5,12	17,6	64,6		
11-May-98	17:30	5,15	17,6	66,4		
12-May-98	7:30	5,73	18,5	63,4	18,2	63,1
12-May-98	8:40	5,78	18,7	64,4		
12-May-98	12:00	5,92	18,4	64,6		
13-May-98	6:55	6,71	18	66,1	18,3	65,2
13-May-98	13:25	6,98	17,6	66,1		
14-May-98	7:35	7,74	17,6	63,9	17,7	65,3
14-May-98	8:13	7,76	17,5	66,5		
14-May-98	13:45	7,99	17	68,2		
15-May-98	17:50	9,16	18,9	65,2	17,8	66,8
16-May-98	12:15	9,93	19,4	65	19,2	65,1
16-May-98	15:35	10,07	19,5	65,8		
17-May-98	16:40	11,11	19,7	65,7	19,6	65,7
18-May-98	15:50	12,08	16,7	70,1	18,2	67,9
19-May-98	15:10	13,05	17,1	68,7	16,9	69,4
20-May-98	7:00	13,71	18,8	65,6	18,0	67,2
21-May-98	11:20	14,89	19,4	65,3	19,1	65,5
22-May-98	9:45	15,83	18,1	66,1	18,8	65,7
23-May-98	13:45	16,99	18	65,8	18,1	66,0
24-May-98	13:45	17,99	17,5	66,3	17,8	66,1
25-May-98	13:45	18,99	17,9	66,8	17,7	66,6
26-May-98	13:45	19,99	17	67,1	17,5	67,0
27-May-98	12:00	20,92	16,7	72,6	16,9	69,9
28-May-98	14:20	22,02	18,9	65,6	17,8	69,1
29-May-98	13:11	22,97	18,7	64,9	18,8	65,3
30-May-98	10:30	23,86	18,8	65,8	18,8	65,4
31-May-98	11:00	24,88	19	67,7	18,9	66,8
1-Jun-98	14:00	26,00	17	68,9	18,0	68,3
2-Jun-98	9:15	26,81	18,4	65,1	17,7	67,0
3-Jun-98	9:25	27,81	18,8	65,9	18,6	65,5
4-Jun-98	9:15	28,81	17,3	66,7	18,1	66,3
				Average conditions :	**18,0**	**66,0**

Table C-5: Environmental conditions of drying regime 6

Date	Time	Time from the start of exposure (days)	Temperature (°C)	Relative humidity (%)	Calculated daily average temp. (°C)	Calculated daily average RH (%)
24-Mar-98	10:00	0,00	19,1	79,7	19,1	79,7
24-Mar-98	15:20	0,22	18,7	83,2		
25-Mar-98	9:30	0,98	17,9	80	18,4	81,6
26-Mar-98	8:00	1,92	18,1	84,4		
26-Mar-98	14:20	2,18	19,3	82	18,0	82,2
27-Mar-98	10:00	3,00	20,4	89,2	19,6	85,0
27-Mar-98	10:20	3,01	19,2	84,2		
27-Mar-98	14:10	3,17	19,2	94,2		
27-Mar-98	14:25	3,18	20,1	86,6		
27-Mar-98	14:45	3,20	17,9	70,3		
27-Mar-98	14:55	3,20	19	84		
27-Mar-98	15:20	3,22	18,7	67,4		
27-Mar-98	15:40	3,24	19,1	80		
27-Mar-98	15:55	3,25	19,1	84,2		
27-Mar-98	16:30	3,27	19,5	82,8		
27-Mar-98	16:45	3,28	19,2	84,8		
28-Mar-98	9:35	3,98	19,4	95,3	19,3	88,8
28-Mar-98	10:32	4,02	19,2	60,6		
28-Mar-98	12:00	4,08	19,1	80,1		
28-Mar-98	13:00	4,13	19	85,4		
28-Mar-98	13:30	4,15	19,2	82		
28-Mar-98	14:30	4,19	18,2	85,5		
29-Mar-98	12:00	5,08	19,4	82,4	18,8	82,9
30-Mar-98	7:00	5,88	19,4	77,7	19,4	80,1
30-Mar-98	10:15	6,01	18,9	81,7		
30-Mar-98	16:40	6,28	19	85,7		
31-Mar-98	7:15	6,89	19	88,6	19,0	85,2
31-Mar-98	10:30	7,02	19,2	82,9		
31-Mar-98	13:30	7,15	18,9	83		
1-Apr-98	6:50	7,87	18,6	88,2	18,8	85,3
1-Apr-98	11:20	8,06	18,6	83,9		
1-Apr-98	13:25	8,14	18,5	85,5		
2-Apr-98	9:25	8,98	18,9	87,1	18,7	86,1
3-Apr-98	11:05	10,05	18,2	81,8	18,6	84,5
3-Apr-98	13:30	10,15	18,3	78,8		
3-Apr-98	15:10	10,22	18,9	81		
4-Apr-98	10:14	11,01	18,8	83,6	18,8	81,9

5-Apr-98	10:45	12,03	18,8	84	18,8	83,8
6-Apr-98	7:50	12,91	18,7	80,6	18,8	82,3
6-Apr-98	11:03	13,04	18,2	79,3		
6-Apr-98	13:20	13,14	18	78		
7-Apr-98	8:22	13,93	17,8	80,7	18,0	79,4
7-Apr-98	9:50	13,99	17,6	79		
7-Apr-98	14:45	14,20	17,7	79,6		
8-Apr-98	10:18	15,01	17,8	80,4	17,7	79,9
8-Apr-98	13:05	15,13	18,2	78,8		
8-Apr-98	14:40	15,19	18,5	77,4		
9-Apr-98	8:00	15,92	19,7	78,9	18,9	78,3
9-Apr-98	9:50	15,99	19,7	79,3		
9-Apr-98	14:15	16,18	20	80,7		
10-Apr-98	9:04	16,96	20,1	86,2	20,0	82,5
10-Apr-98	15:40	17,24	20,5	82,2		
11-Apr-98	10:03	18,00	20,4	83,1	20,4	83,1
11-Apr-98	14:15	18,18	20,5	85,8		
11-Apr-98	16:30	18,27	20,7	79,2		
12-Apr-98	11:45	19,07	20,8	84,7	20,7	82,4
12-Apr-98	12:25	19,10	21,1	81,6		
12-Apr-98	13:40	19,15	21,1	83,7		
13-Apr-98	11:15	20,05	21,2	85,9	21,1	84,6
14-Apr-98	10:10	21,01	21,4	85,2	21,3	85,6
14-Apr-98	13:00	21,13	19,5	81,1		
14-Apr-98	14:35	21,19	19,3	81,3		
15-Apr-98	9:30	21,98	19	80,3	19,3	81,1
15-Apr-98	13:40	22,15	18,6	80,7		
16-Apr-98	12:55	23,12	18,7	77,4	18,7	79,3
17-Apr-98	9:10	23,97	18,7	77,1	18,7	77,3
17-Apr-98	12:17	24,10	19	78,6		
18-Apr-98	13:20	25,14	18,7	75,8	18,9	77,3
19-Apr-98	9:25	25,98	20,7	78,5	19,7	77,2
20-Apr-98	7:45	26,91	18,6	79,1	19,7	78,8
21-Apr-98	7:47	27,91	18,5	78,3	18,6	78,7
22-Apr-98	7:45	28,91	19	74,7	18,8	76,5
				Average conditions :	**19,1**	**82,0**

Table C-6: Environmental conditions for the two wind speed investigations (wind speed was consatnt at 5,6 m/s)

20 MPa concrete, wet cured for 1 day			40 MPa concrete, wet cured for 7 days		
Date	**Temperature (°C)**	**Relative humidity (%)**	**Date**	**Temperature (°C)**	**Relative humidity (%)**
24-Mar-98	25,5	63,2	6-May-98	19,1	55,3
25-Mar-98	23,2	72,2	7-May-98	19	53,5
26-Mar-98	24,5	68,7	8-May-98	19	51,2
27-Mar-98	25,5	66,6	9-May-98	20	61,2
28-Mar-98	25,4	62,1	10-May-98	20,9	67,5
29-Mar-98	25,6	61,5	11-May-98	20,4	65,5
30-Mar-98	19	65,5	12-May-98	20,7	66,9
31-Mar-98	19,5	55	13-May-98	18,3	53,5
1-Apr-98	19	70	14-May-98	18,7	54,2
2-Apr-98	19,5	65	15-May-98	18,9	55,2
3-Apr-98	19,5	61	16-May-98	19,2	54
4-Apr-98	19	50	17-May-98	19,1	55,3
5-Apr-98	19	49	18-May-98	17,2	64
6-Apr-98	18	54	19-May-98	17,2	57,3
7-Apr-98	19	47	20-May-98	17,4	55,2
8-Apr-98	18,5	48	21-May-98	17,4	56,7
9-Apr-98	18	53	22-May-98	17,4	57,2
10-Apr-98	19	46	23-May-98	17,4	52,9
11-Apr-98	19	52	24-May-98	17,3	52,6
12-Apr-98	19	69	25-May-98	17,8	48
13-Apr-98	19,5	56	26-May-98	18,5	54,1
14-Apr-98	20,5	73,5	27-May-98	18	57
Average conditions:	**20,7**	**59,5**	**Average conditions:**	**18,6**	**56,7**

APPENDIX D - MOISTURE LOSSES UNDER THE DIFFERENT ENVIRONMENTAL CONDITIONS

The moisture losses of environments 2 to 6 are given in Tables D-1 to D-5, with the moisture losses of the two wind speed investigations in Table D-6.

Table D-1: Moisture losses in environment 2

Concrete grade (MPa)	Period of wet curing (days)	Time since start of exposure (days)	Moisture loss (%)	Moisture loss (grams)
20	1	0,00	0,00	0,00
		1,00	2,74	56,58
		2,04	3,23	66,66
		3,03	3,52	72,78
		4,03	3,74	77,20
		5,13	3,94	81,36
		6,06	4,07	84,06
		7,00	4,15	88,08
		26,87	4,91	101,56
20	3	0,00	0,00	0,00
		1,03	1,91	39,74
		2,00	2,25	46,72
		2,95	2,45	50,96
		4,03	2,66	55,24
		5,03	2,83	58,92
		6,00	2,96	61,54
		6,87	3,07	63,80
		24,82	4,01	83,46
20	7	0,00	0,00	0,00
		0,99	1,69	34,58
		2,03	2,04	41,82
		3,04	2,23	45,54
		4,01	2,40	49,18
		4,82	2,55	52,16
		6,04	2,70	55,22
		7,04	2,86	58,42
		20,80	3,81	78,02
40	1	0,00	0,00	0,00
		1,05	1,62	33,98
		2,04	1,93	40,48

		3,04	2,10	43,88
		4,13	2,24	47,00
		5,08	2,37	49,70
		6,06	2,47	51,82
		7,10	2,57	53,88
		26,89	3,54	74,18
40	3	0,00	0,00	0,00
		1,03	1,31	27,44
		2,00	1,60	33,56
		2,95	1,74	36,38
		4,03	1,84	38,48
		5,03	1,98	41,44
		6,00	2,10	43,98
		6,87	2,20	46,06
		24,81	3,11	65,20
40	7	0,00	0,00	0,00
		1,05	1,02	20,54
		2,05	1,22	24,62
		3,03	1,39	28,16
		3,77	1,50	30,34
		5,06	1,70	34,34
		6,06	1,83	37,00
		7,03	1,92	38,72
		20,82	2,69	54,46
60	1	0,00	0,00	0,00
		0,99	1,02	20,64
		1,99	1,25	25,22
		3,09	1,45	29,44
		4,04	1,59	32,28
		5,02	1,68	34,04
		6,05	1,76	35,62
		7,05	1,81	36,64
		26,84	2,75	55,66
60	3	0,00	0,00	0,00
		1,11	0,84	17,12
		2,05	1,04	21,34
		3,04	1,16	23,82
		4,07	1,25	25,50
		5,08	1,31	26,88
		6,06	1,41	28,88
		7,00	1,48	31,10
		24,85	2,14	43,80
60	7	0,00	0,00	0,00
		1,02	0,70	14,28
		1,99	0,85	17,46
		2,95	0,98	20,10

		4,03	1,09	22,46
		5,03	1,20	24,72
		5,99	1,28	26,32
		6,87	1,36	27,86
		20,79	1,88	38,70

Table D-2: Moisture losses in environment 3

Concrete grade (MPa)	Period of wet curing (days)	Time since start of exposure (days)	Moisture loss (%)	Moisture loss (grams)
20	1	0,00	0,00	0,00
		0,99	1,84	35,30
		1,99	2,31	44,36
		3,00	2,50	47,98
		4,01	2,69	51,62
		5,12	2,85	54,00
		5,93	2,91	55,80
		7,00	2,97	56,92
		7,95	3,02	57,88
		26,80	3,99	76,54
20	3	0,00	0,00	0,00
		1,01	1,52	29,90
		2,02	1,88	36,94
		2,95	2,09	41,20
		3,95	2,24	44,04
		4,98	2,36	46,36
		5,99	2,46	48,46
		6,92	2,54	50,04
		24,81	3,48	68,56
20	7	0,00	0,00	0,00
		1,03	1,34	26,18
		2,06	1,66	32,44
		2,99	1,82	35,56
		4,06	2,00	39,20
		5,10	2,14	41,94
		6,07	2,26	44,16
		7,03	2,35	46,00
		20,88	3,22	63,12
40	1	0,00	0,00	0,00
		1,00	1,33	25,08
		2,01	1,59	29,82
		3,02	1,77	33,32

		3,95	1,89	35,20
		4,95	1,99	37,48
		5,97	2,07	38,84
		6,99	2,13	40,10
		26,81	2,97	55,80
40	3	0,00	0,00	0,00
		1,03	1,12	21,00
		2,10	1,41	26,50
		2,95	1,54	28,76
		3,98	1,70	31,68
		5,00	1,82	34,02
		5,93	1,91	35,64
		7,01	2,00	37,44
		24,83	2,80	53,38
40	7	0,00	0,00	0,00
		1,02	0,89	16,90
		1,95	1,09	20,66
		3,03	1,23	23,46
		4,06	1,36	25,84
		5,03	1,46	27,72
		5,99	1,53	29,14
		7,00	1,62	30,85
		8,09	1,69	32,22
		20,84	2,30	43,68
60	1	0,00	0,00	0,00
		1,01	0,81	15,70
		2,02	0,99	19,22
		3,14	1,10	21,44
		3,95	1,19	23,18
		4,97	1,26	24,60
		5,99	1,33	25,94
		6,91	1,39	26,98
		26,80	2,16	41,96
60	3	0,00	0,00	0,00
		1,12	1,00	18,00
		1,93	1,12	21,36
		2,96	1,23	23,36
		3,97	1,32	25,10
		4,91	1,41	26,86
		5,99	1,51	28,68
		7,10	1,58	29,96
		24,79	2,28	43,30
60	7	0,00	0,00	0,00
		0,94	0,60	11,56
		2,11	0,77	14,82
		3,06	0,88	16,90

		4,03	0,96	18,46
		4,99	1,02	19,70
		5,93	1,08	20,00
		7,09	1,15	21,00
		20,83	1,70	32,72

Table D-3: Moisture losses in environment 4

Concrete grade (MPa)	Period of wet curing (days)	Time since start of exposure (days)	Moisture loss (%)	Moisture loss (grams)
20	1	0,00	0,00	0,00
		0,91	0,88	16,88
		1,90	1,61	30,82
		2,93	2,11	40,46
		3,78	2,34	44,92
		4,71	2,51	48,10
		5,71	2,63	50,58
		6,72	2,72	52,24
		26,74	3,47	66,56
20	3	0,00	0,00	0,00
		1,04	1,11	21,80
		1,89	1,74	34,10
		2,82	2,08	40,80
		3,83	2,28	44,82
		4,83	2,41	47,38
		6,02	2,54	49,86
		7,04	2,64	51,76
		24,86	3,37	68,40
20	7	0,00	0,00	0,00
		1,01	1,07	21,40
		2,20	1,60	31,84
		3,23	1,85	36,76
		4,14	1,97	39,28
		5,19	2,11	41,94
		6,07	2,22	44,16
		7,01	2,31	45,88
		21,04	3,10	61,66
40	1	0,00	0,00	0,00
		0,99	0,90	16,80
		2,03	1,36	25,24
		2,87	1,56	28,96
		3,80	1,70	31,56

		4,80	1,80	33,52
		5,81	1,87	34,84
		7,00	1,93	35,98
		26,77	2,50	46,48
40	3	0,00	0,00	0,00
		0,85	0,82	16,34
		1,79	1,10	21,98
		2,79	1,26	25,04
		3,79	1,35	26,94
		4,98	1,44	28,64
		6,01	1,51	30,06
		6,92	1,55	30,86
		24,75	2,13	42,46
40	7	0,00	0,00	0,00
		1,19	0,78	15,54
		2,22	0,97	19,32
		3,13	1,06	21,12
		4,15	1,16	23,14
		5,07	1,25	24,94
		6,00	1,31	26,16
		7,01	1,40	28,08
		20,96	1,89	37,84
60	1	0,00	0,00	0,00
		1,04	0,71	13,92
		1,89	0,91	17,78
		2,82	1,03	20,22
		3,82	1,12	22,00
		4,83	1,18	23,22
		6,02	1,23	24,26
		7,04	1,28	25,20
		26,81	1,69	33,30
60	3	0,00	0,00	0,00
		0,94	0,64	12,16
		1,94	0,82	15,64
		2,94	0,91	17,36
		4,14	0,99	18,98
		5,16	1,05	20,16
		6,07	1,09	20,82
		7,13	1,13	21,66
		24,92	1,55	32,08
60	7	0,00	0,00	0,00
		1,02	0,55	10,74
		1,93	0,65	12,74
		2,98	0,74	14,46
		3,87	0,81	15,88
		4,80	0,86	16,84

APPENDIX D - MOISTURE LOSSES UNDER THE DIFFERENT ENVIRONMENTAL CONDITIONS

40	3	0,00	0,00	0,00
		1,02	0,73	14,74
		1,92	0,99	19,84
		2,82	1,13	22,62
		3,75	1,23	24,60
		4,77	1,29	25,94
		6,21	1,37	27,46
		6,97	1,41	28,38
		24,85	1,89	37,88
40	7	0,00	0,00	0,00
		1,00	0,65	12,92
		2,44	0,90	17,86
		3,20	0,99	19,52
		4,38	1,09	21,62
		5,09	1,15	22,81
		6,32	1,21	24,00
		6,98	1,25	24,68
		21,08	1,69	33,4
60	1	0,00	0,00	0,00
		0,98	0,71	13,98
		1,99	0,99	19,58
		2,89	1,12	22,16
		3,83	1,19	23,56
		4,72	1,26	24,86
		5,74	1,30	25,72
		7,18	1,35	26,7
		26,82	1,74	34,38
60	3	0,00	0,00	0,00
		0,91	0,60	11,86
		1,81	0,77	15,14
		2,74	0,87	17,16
		3,76	0,94	18,54
		5,19	1,01	19,96
		5,95	1,04	20,62
		7,14	1,11	21,86
		24,83	1,48	29,24
60	7	0,00	0,00	0,00
		1,41	0,53	10,96
		2,17	0,61	12,58
		3,36	0,70	14,42
		4,07	0,74	15,23
		5,29	0,79	16,26
		5,96	0,81	16,76
		6,99	0,85	17,6
		21,05	1,16	23,84

		5,80	0,94	18,42
		6,80	0,99	19,40
		20,78	1,33	25,94

Table D-4: Moisture losses in environment 5

Concrete grade (MPa)	Period of wet curing (days)	Time since start of exposure (days)	Moisture loss (%)	Moisture loss (grams)
20	1	0,00	0,00	0,00
		0,98	0,62	11,52
		2,00	1,23	22,94
		2,97	1,74	32,64
		3,99	2,11	39,50
		4,89	2,30	43,04
		5,79	2,41	45,06
		6,72	2,51	47,00
		26,81	3,18	59,56
20	3	0,00	0,00	0,00
		0,98	0,77	14,84
		1,99	1,37	26,56
		2,90	1,77	34,34
		3,84	2,00	38,86
		4,72	2,16	41,94
		5,75	2,26	44,00
		7,18	2,39	46,36
		24,81	3,09	60,52
20	7	0,00	0,00	0,00
		0,93	0,72	22,94
		1,96	1,55	29,56
		3,39	1,82	34,72
		4,15	1,92	36,74
		5,33	2,06	39,42
		6,04	2,14	10,87
		7,27	2,22	42,40
		21,02	2,83	54,1
40	1	0,00	0,00	0,00
		1,03	0,82	17,02
		2,00	1,25	25,80
		3,01	1,49	30,68
		3,92	1,60	33,06
		4,82	1,68	34,60
		5,74	1,75	36,02
		6,77	1,79	36,98
		26,84	2,29	47,18

APPENDIX F - DERIVATION OF EMPIRICAL FORMULAE TO ESTIMATE THE DEGREE OF HYDRATION

In Chapter 9, a theory was formulated to estimate the effect of drying processes on the capillary porosity of hardened concrete. Part of this theory was concerned with the approximation of degree of hydration, as a function of time and w:c ratio. The formulae used were derived from experimental data by Soroka [1979]. The method used to accomplish this is subsequently discussed.

F.1. Experimental data used

The plot of degree of hydration versus time (as functions of different w:c ratios) used to derive the empirical formulae, is given in Figure F-1. The degree of hydration in this figure is given as the combined water content of the cement paste (w_n:c), and can be converted to a percentage by dividing by a w_n:c ratio of 0,23 kg of combined water / kg of cement [Soroka, 1979].

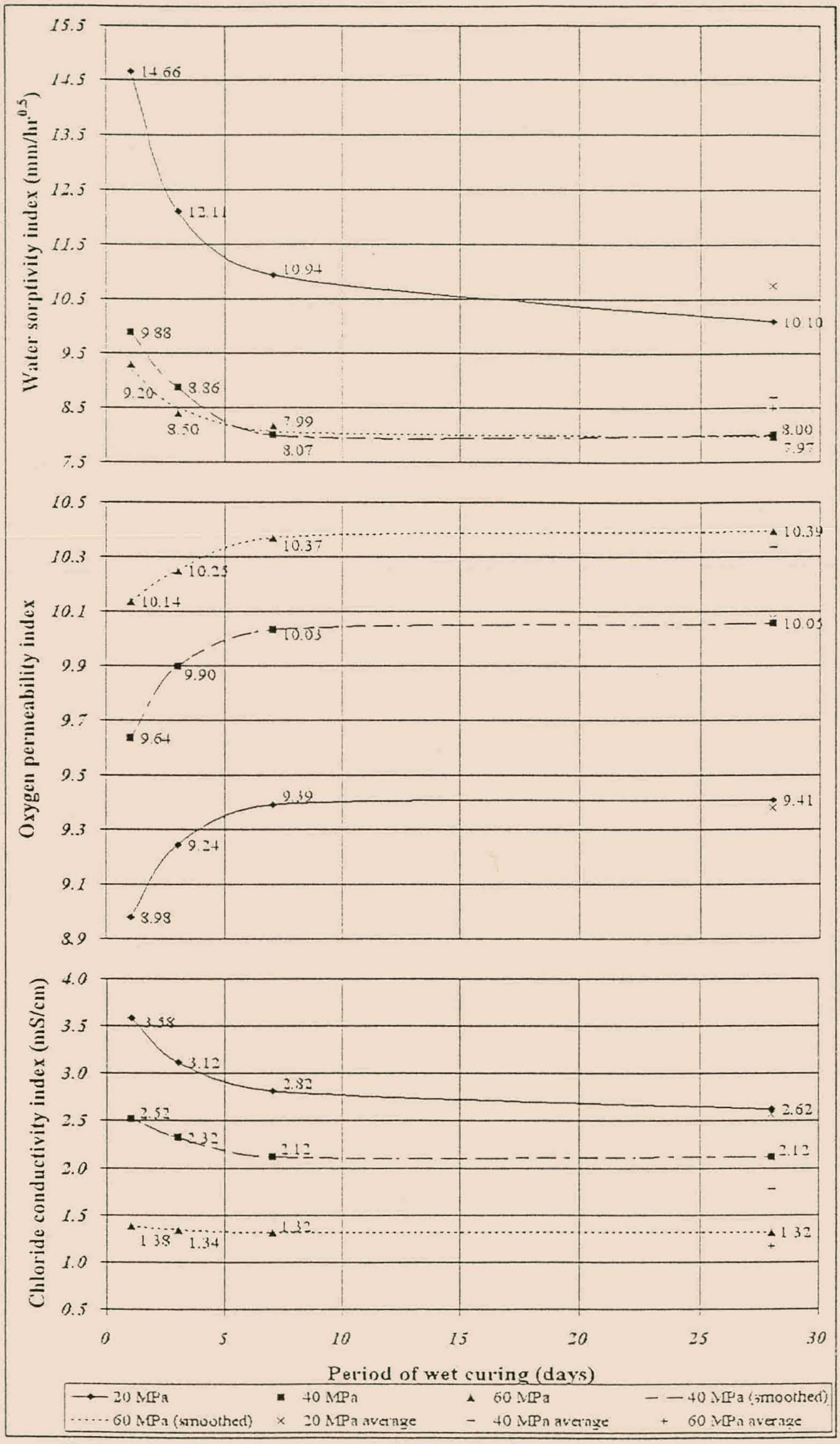

Figure E-8: Smoothed durability indexes obtained from environment 4 (18,8°C, 54,0% RH

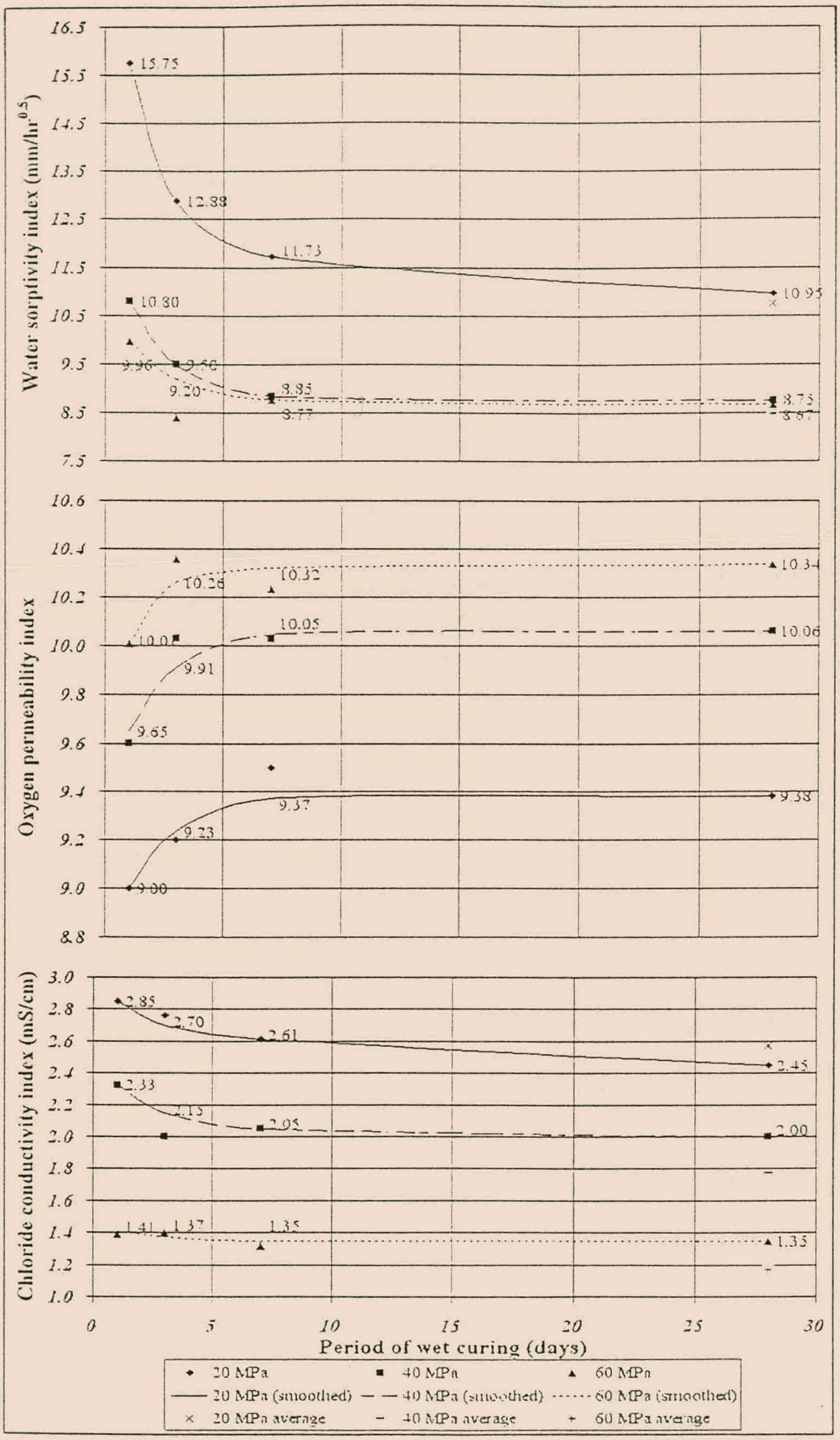

Figure E-9: Smoothed durability indexes obtained from environment 5 (18,0°C, 66,0% RH)

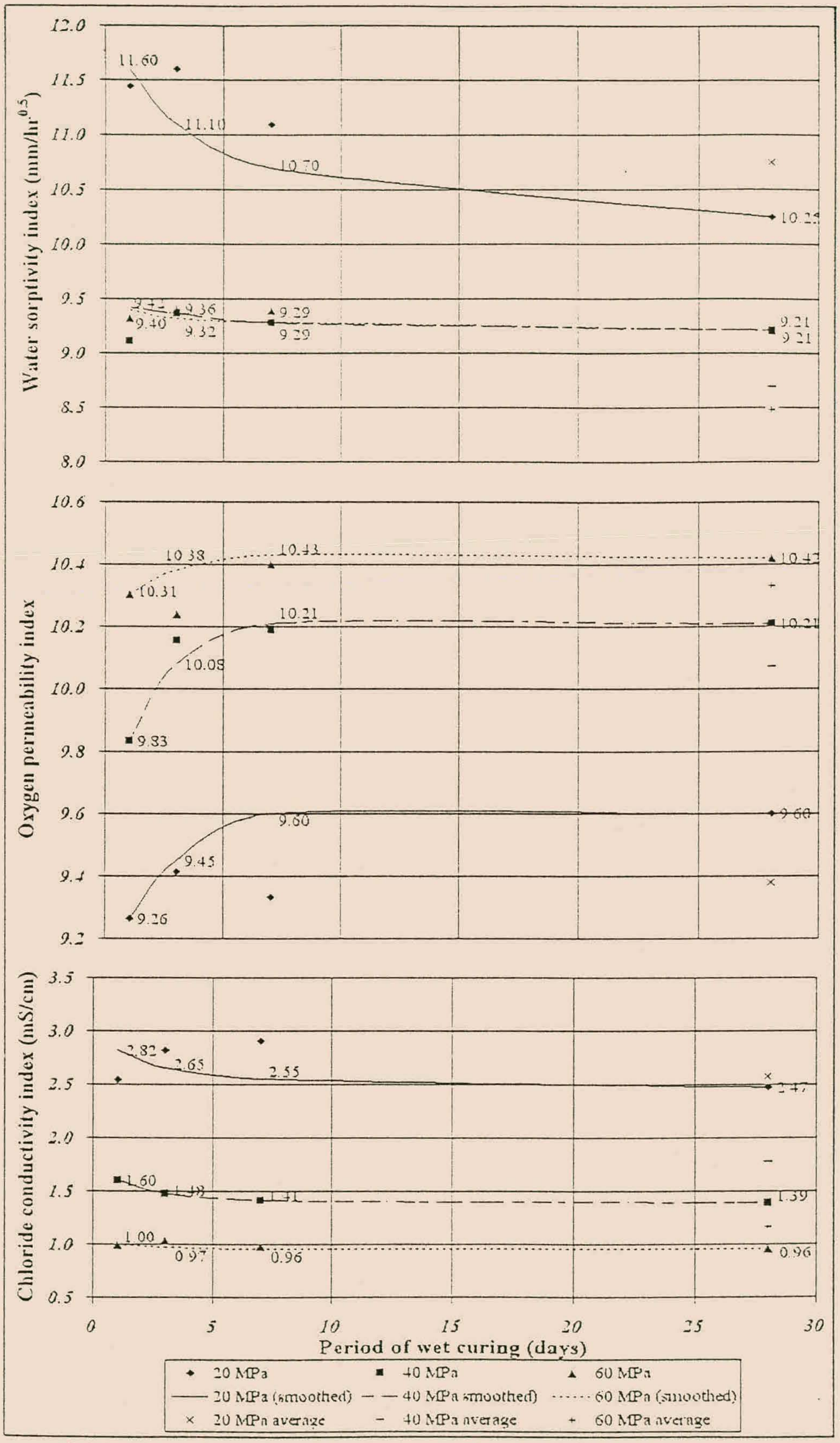

Figure E-10: Smoothed durability indexes obtained from environment 6 (18,8°C, 82,0% RH)

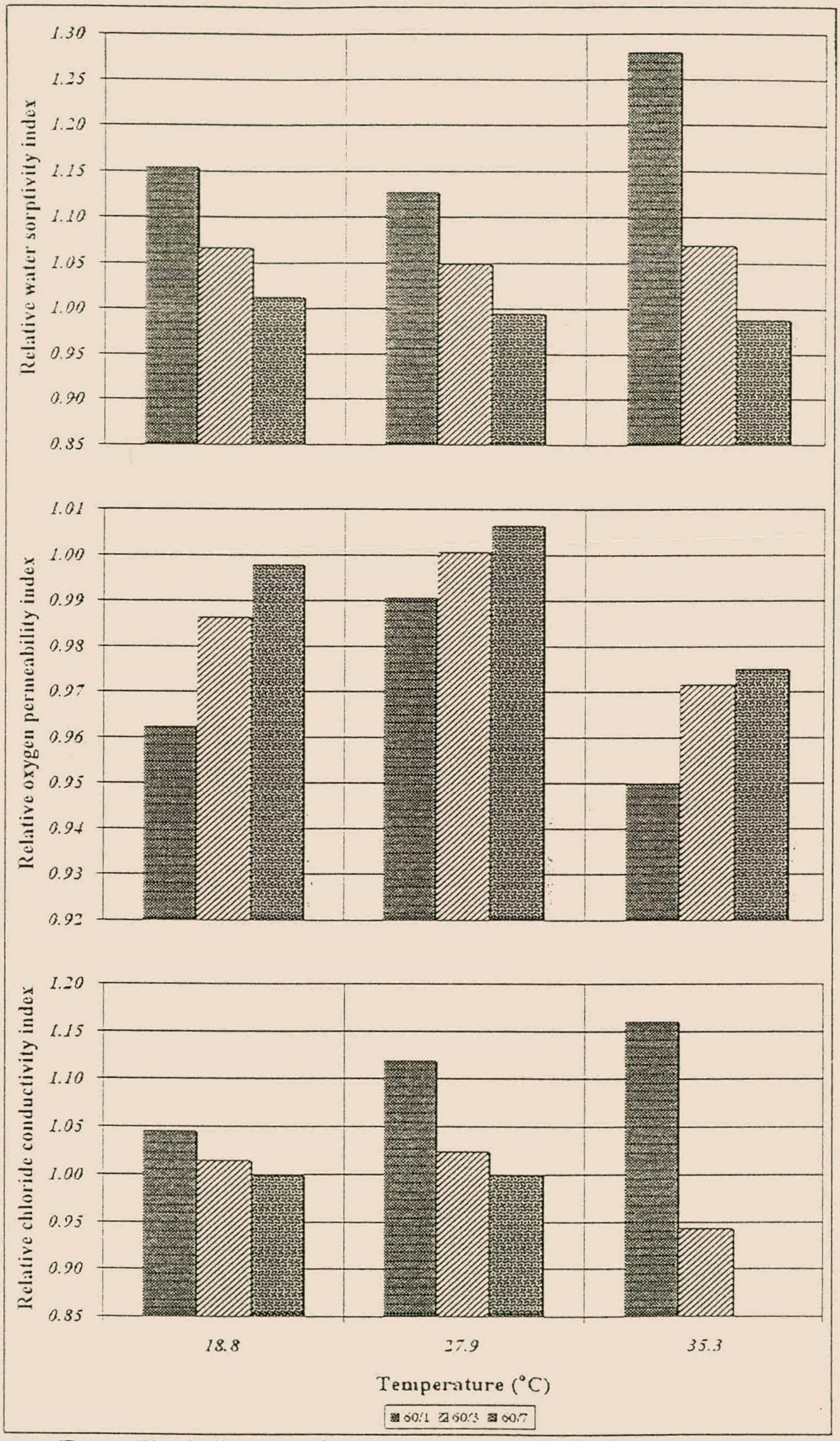

Figure E-11: The influence of temperature on the durability indexes of 60 MPa concretes

Table D-5: Moisture losses in environment 6

Concrete grade (MPa)	Period of wet curing (days)	Time since start of exposure (days)	Moisture loss (%)	Moisture loss (grams)
20	1	0,00	0,00	0,00
		0,98	0,40	7,38
		1,99	0,61	11,38
		2,99	0,78	14,48
		3,95	0,96	17,88
		5,16	1,22	22,73
		5,85	1,36	25,30
		7,00	1,44	27,74
		7,99	1,49	28,70
		26,84	2,27	42,44
20	3	0,00	0,00	0,00
		0,99	0,26	5,20
		1,94	0,47	9,34
		2,97	0,90	17,72
		3,85	1,19	23,42
		4,98	1,37	26,90
		5,86	1,48	29,16
		7,00	1,60	32,98
		7,98	1,68	34,63
		24,83	2,32	45,68
20	7	0,00	0,00	0,00
		1,16	0,51	10,16
		2,03	0,76	15,06
		3,12	1,03	20,56
		4,16	1,21	24,08
		5,09	1,35	26,87
		6,14	1,46	29,18
		7,31	1,55	30,96
		21,01	2,10	41,90
40	1	0,00	0,00	0,00
		1,01	0,31	6,12
		2,01	0,48	9,34
		2,96	0,63	12,28
		4,00	0,80	15,59
		4,87	0,89	17,52
		6,01	0,95	18,72
		6,89	1,00	19,62
		26,88	1,46	28,58
40	3	0,00	0,00	0,00
		0,95	0,44	8,32

Appendix D - Moisture Losses Under the Different Environmental Conditions

		2,13	0,73	13,80
		2,86	0,87	16,38
		4,00	0,94	17,60
		4,87	0,98	18,38
		5,96	1,01	18,94
		7,00	1,06	19,98
		24,87	1,46	27,52
40	7	0,00	0,00	0,00
		1,03	0,37	6,74
		2,16	0,75	13,78
		3,16	0,78	14,33
		4,14	0,82	15,07
		5,14	0,90	16,52
		6,14	0,96	17,66
		7,03	1,01	18,44
		21,03	1,39	25,50
60	1	0,00	0,00	0,00
		0,99	0,23	4,70
		1,94	0,38	7,54
		2,85	0,47	9,42
		3,85	0,53	10,62
		4,99	0,56	11,16
		5,87	0,58	11,70
		7,00	0,60	12,44
		7,98	0,62	12,85
		26,86	0,81	16,36
60	3	0,00	0,00	0,00
		1,22	0,40	7,69
		1,91	0,51	9,80
		3,05	0,53	10,30
		4,00	0,56	10,74
		5,01	0,58	11,12
		6,04	0,60	11,60
		7,00	0,62	11,89
		8,03	0,64	12,40
		24,92	0,84	16,20
60	7	0,00	0,00	0,00
		1,14	0,25	4,80
		2,18	0,42	8,06
		3,25	0,49	9,16
		4,16	0,52	9,90
		5,16	0,55	10,56
		6,05	0,58	11,06
		7,13	0,61	11,60
		21,06	0,81	15,42

Table D-6: Moisture losses during the two wind speed investigations

Concrete grade (MPa) and period of wet curing	Drying under controlled wind / still air conditions	Time since start of exposure (days)	Moisture loss (%)	Moisture loss (grams)
20/1	Wind	0,00	0,00	0,00
		0,92	2,40	46,73
		1,93	2,70	52,55
		3,00	2,82	54,93
		4,04	2,91	56,68
		5,14	2,98	58,08
		6,02	3,03	58,98
		6,91	3,06	59,70
		7,91	3,10	60,32
		22,93	3,52	68,63
20/1	Still air	0,00	0,00	0,00
		0,92	1,63	32,35
		1,93	2,18	43,33
		3,00	2,34	46,57
		4,04	2,45	48,75
		5,14	2,54	50,58
		6,02	2,59	51,60
		6,91	2,64	52,53
		7,91	2,68	53,30
		22,93	3,15	62,70
40/7	Wind	0,00	0,00	0,00
		1,19	0,84	16,15
		2,22	1,01	19,48
		3,13	1,10	21,23
		4,20	1,18	22,75
		5,07	1,25	24,00
		6,00	1,31	25,23
		7,01	1,38	26,58
		8,00	1,44	27,63
		20,97	1,88	36,18
40/7	Still air	0,00	0,00	0,00
		1,19	0,85	15,90
		2,22	1,01	18,98
		3,13	1,10	20,65
		4,20	1,18	22,08
		5,07	1,25	23,40
		6,00	1,31	24,53
		7,01	1,38	25,83
		8,00	1,43	26,80
		20,97	1,86	34,85

APPENDIX E - RESULTS OF THE DURABILITY INDEX TESTS

In Chapter 7 the results of the durability index tests were given. Due to experimental scatter, some results from environments 2 to 6 were slightly adjusted, or smoothed, to fit general trends. In Figures C-1 to C-5 the actual index measurements from environments 2 to 6 are illustrated, with the smoothed results in Figures C-6 to C-10. In Figure C-11 the influence of temperature, on the 60 MPa concretes, is illustrated.

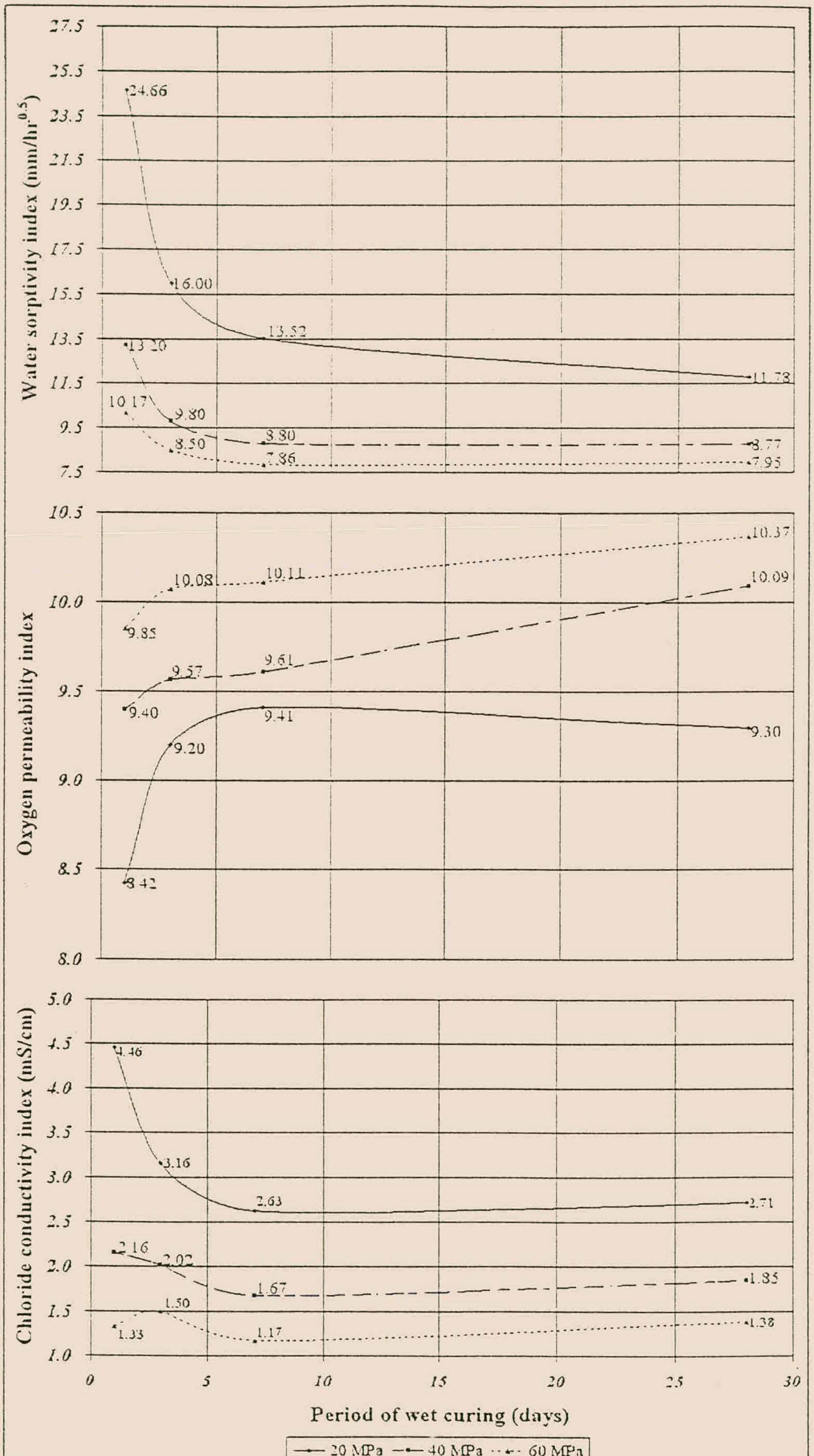

Figure E-1: Durability indexes obtained from environment 2 (35,3°C, 51,5% RH)

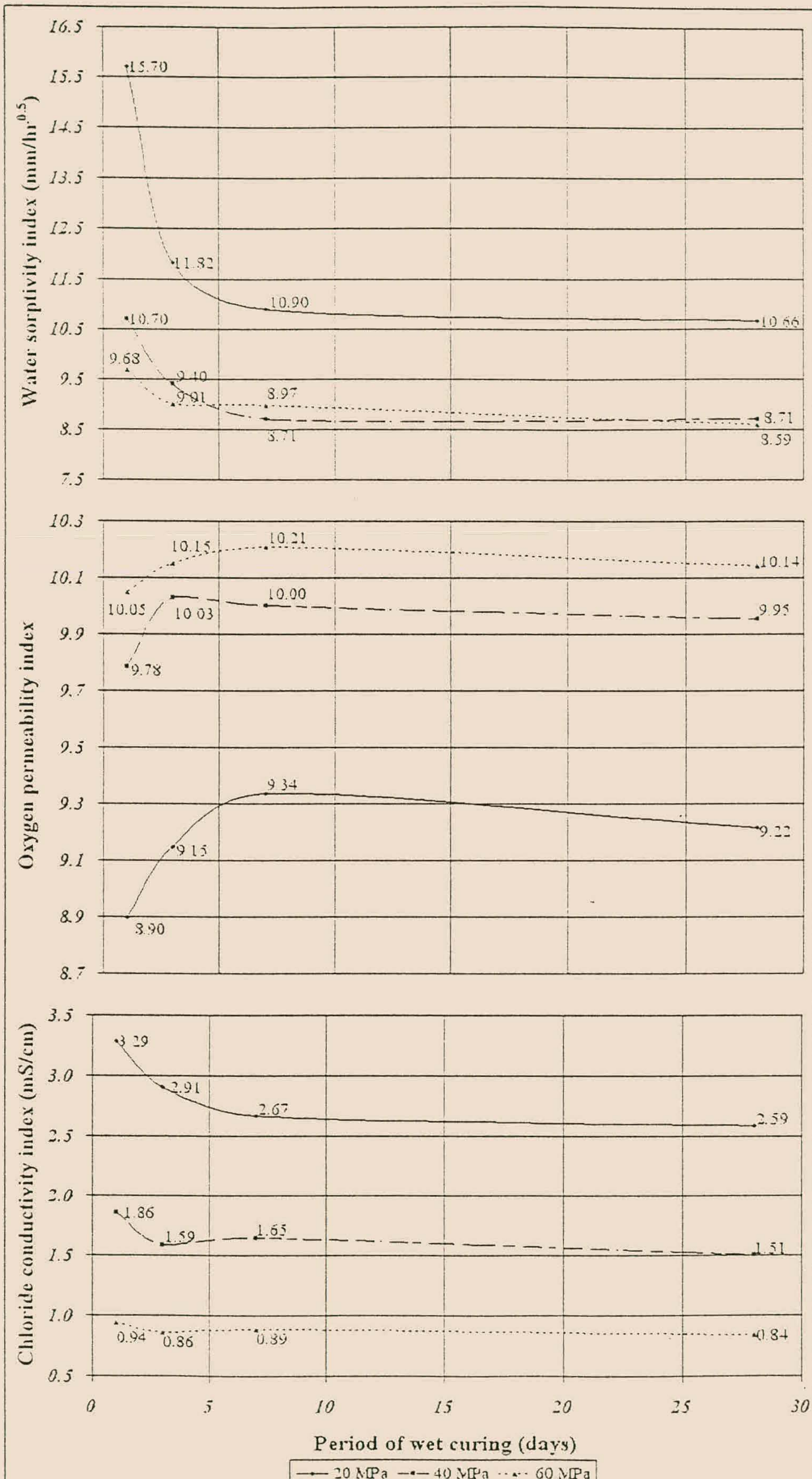

Figure E-2: Durability indexes obtained from environment 3 (27,9°C, 52,5% RH)

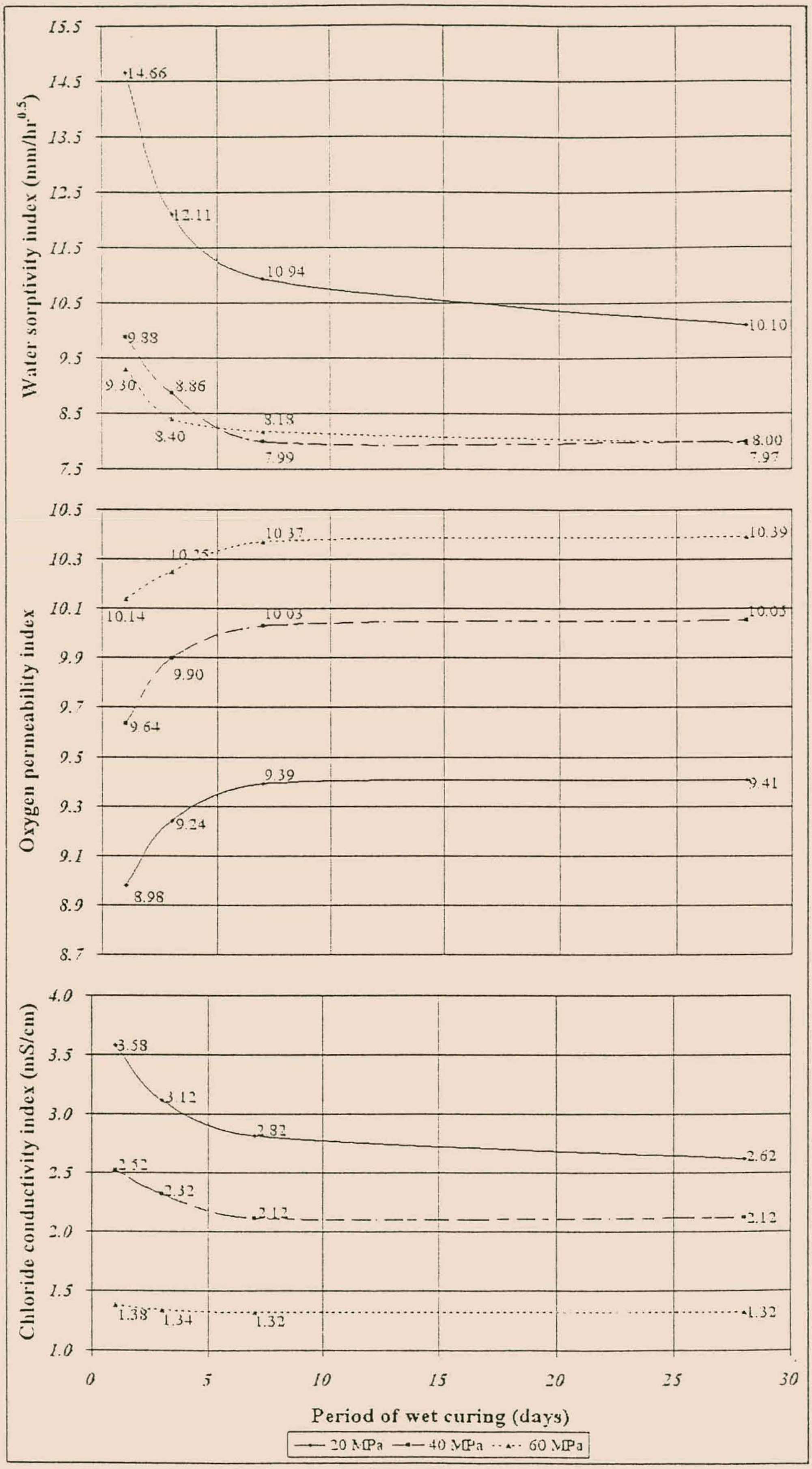

Figure E-3: Durability indexes obtained from environment 4 (18,8°C, 54,0% RH)

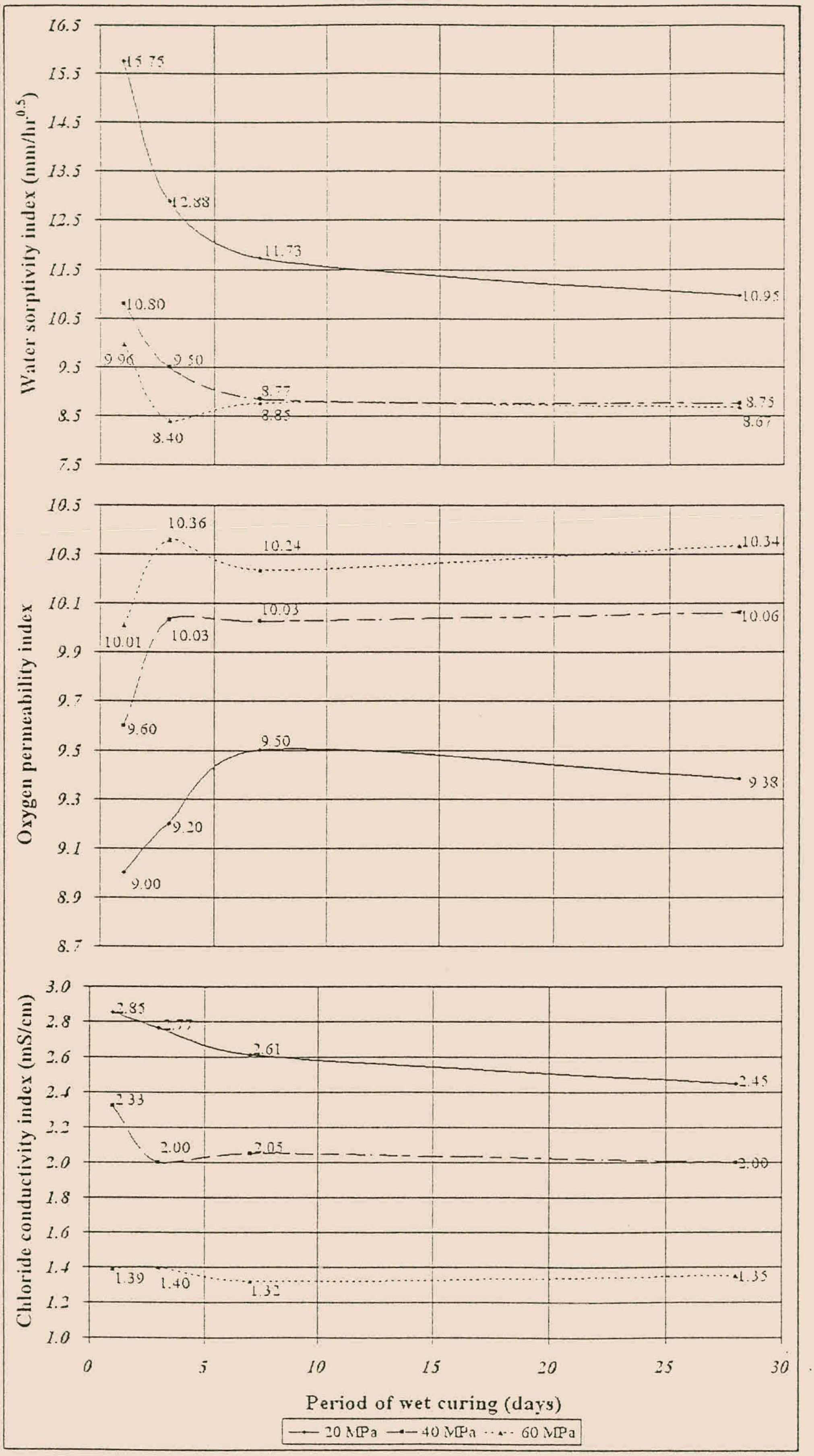

Figure E-4: Durability indexes obtained from environment 5 (18,0°C, 66,0% RH)

APPENDIX E - THE RESULTS OF THE DURABILITY INDEX TESTS

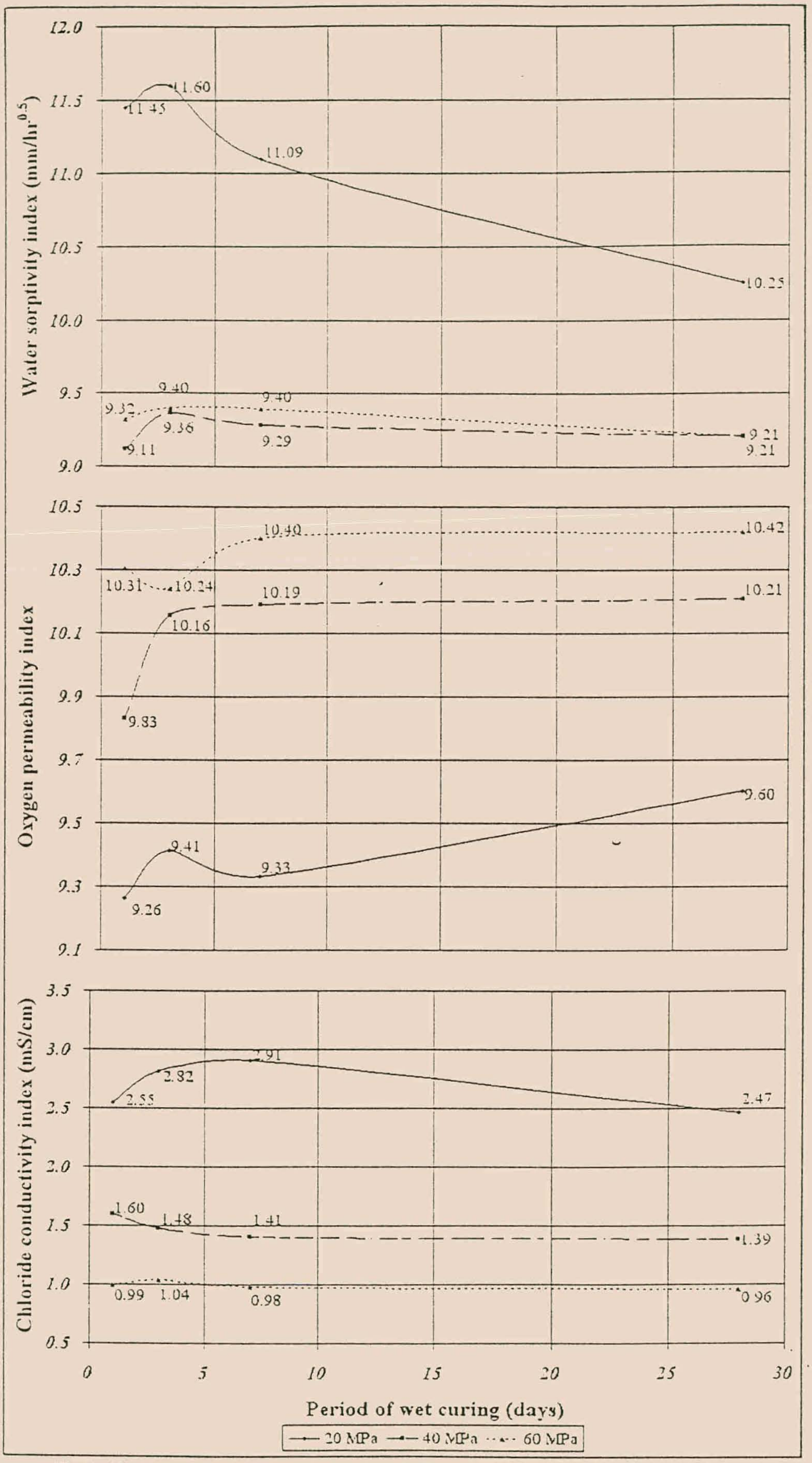

Figure E-5: Durability indexes obtained from environment 6 (19,1°C, 82,0% RH)

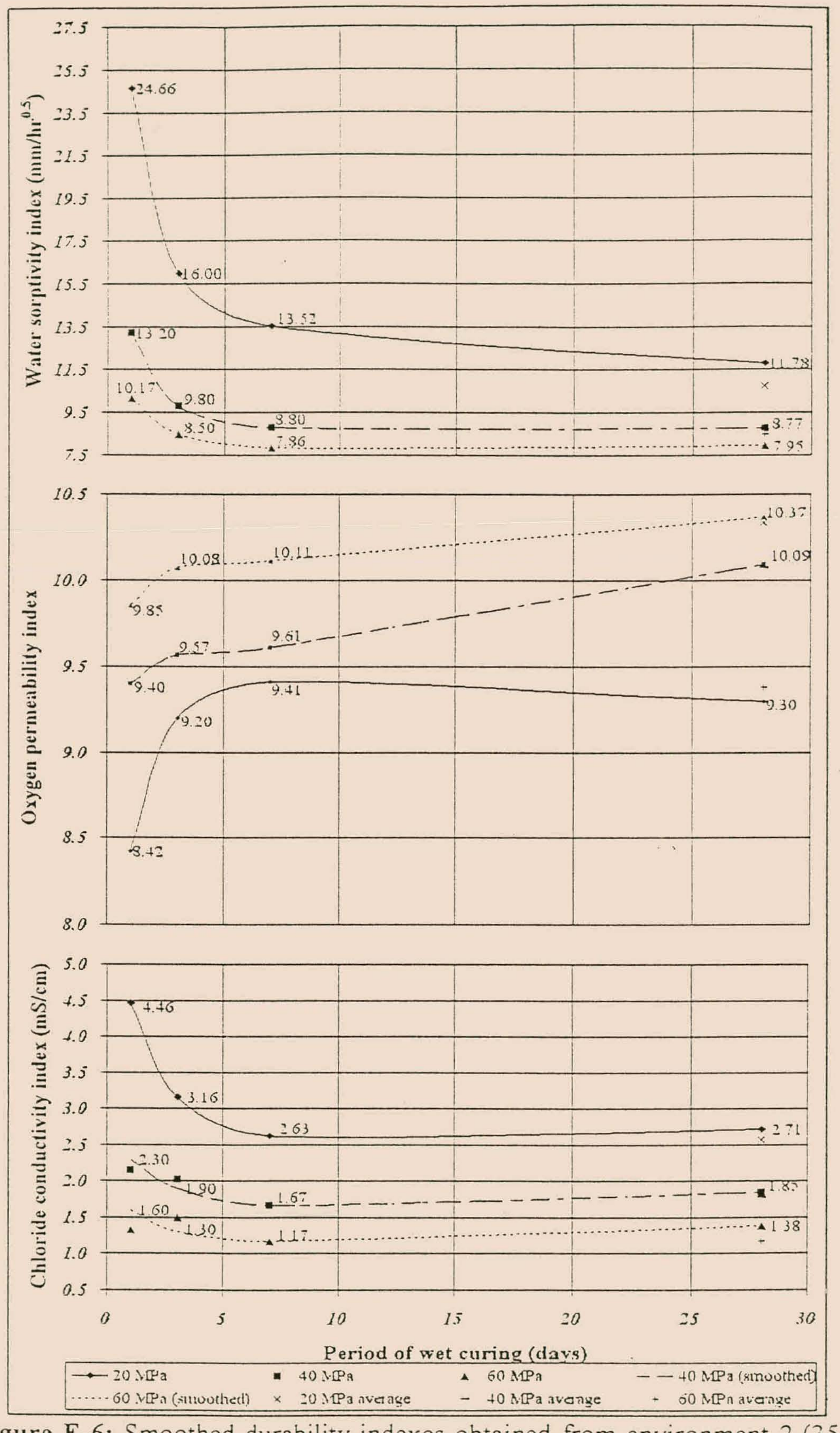

Figure E-6: Smoothed durability indexes obtained from environment 2 (35,3°C, 51,5% RH)

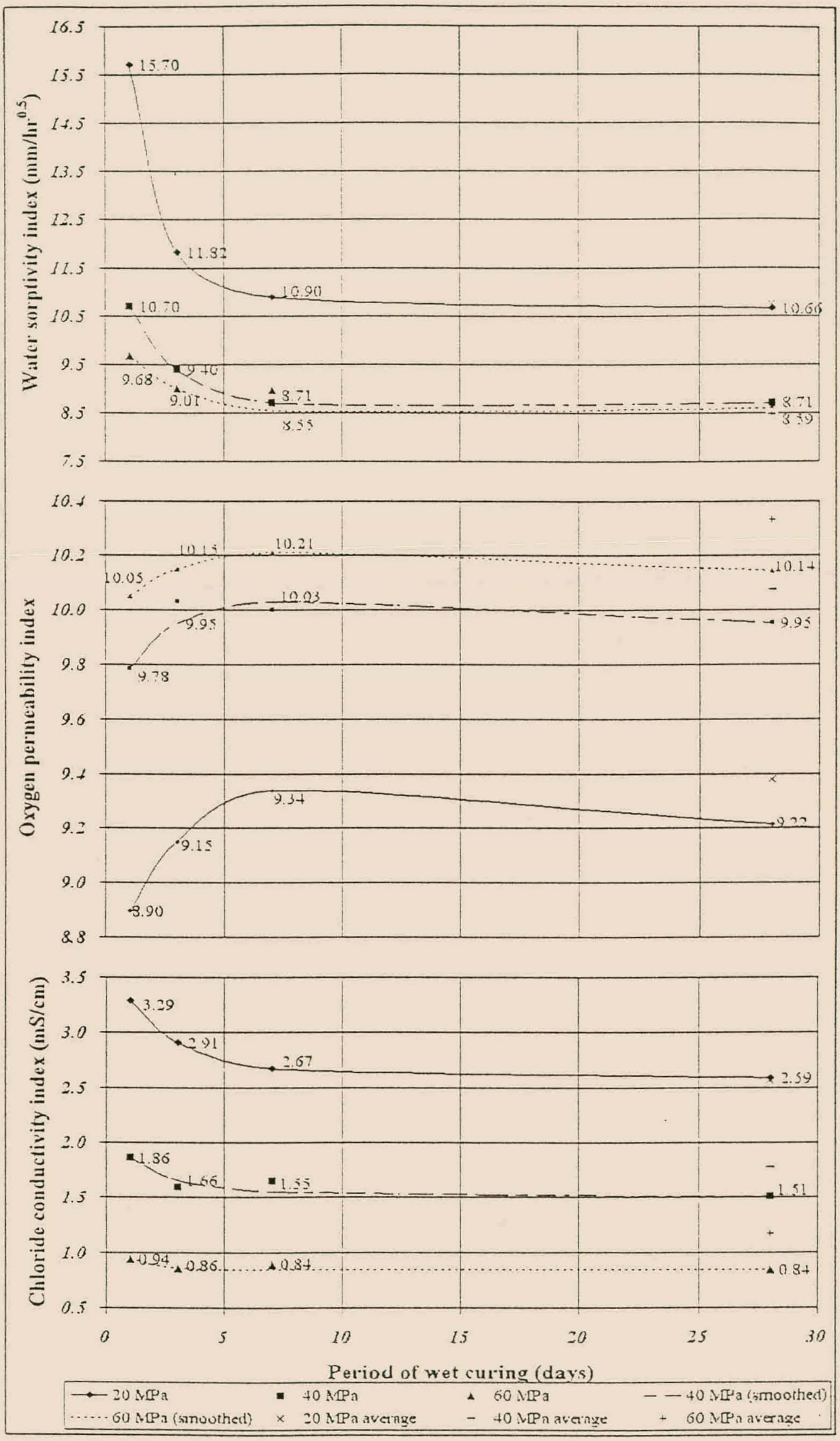

Figure E-7: Smoothed durability indexes obtained from environment 3 (27,9°C, 52,5% RH)

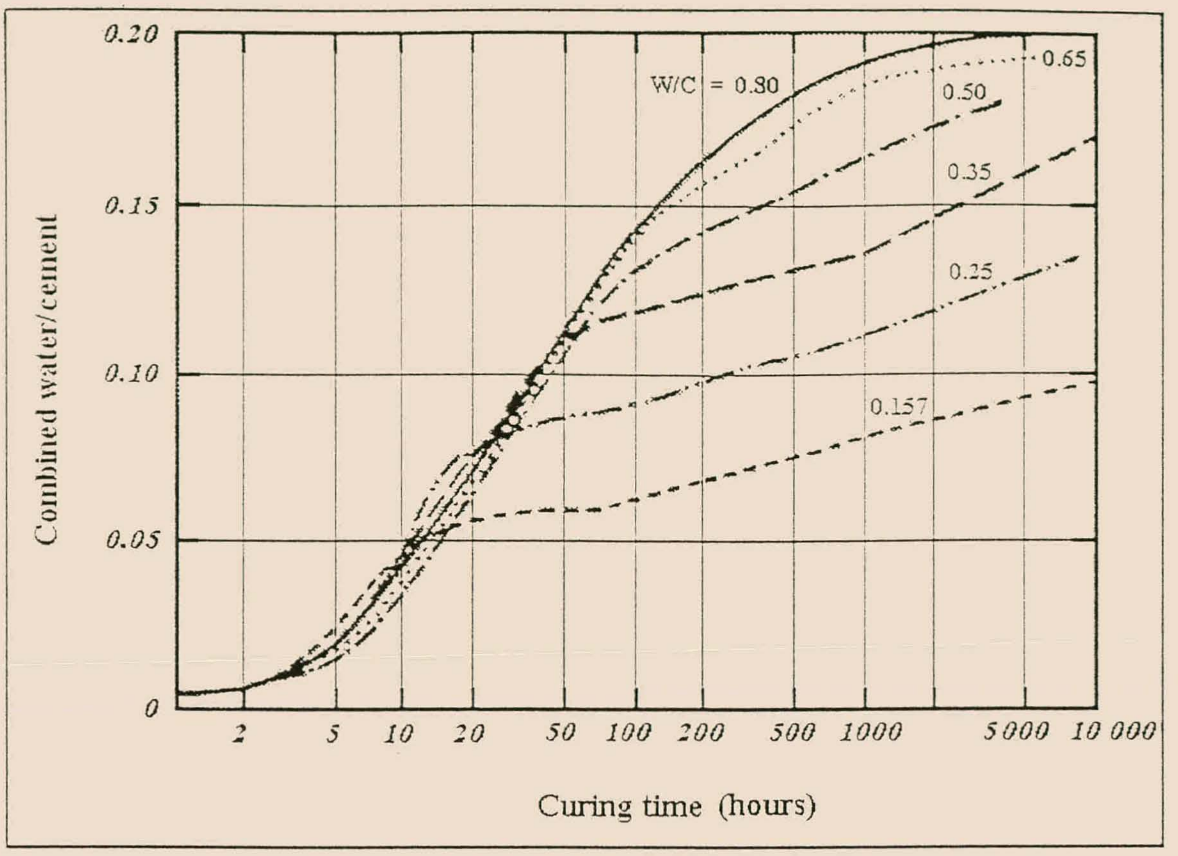

Figure F-1: Degree of hydration as a function of time and w:c ratio [Soroka, 1979]

F.2. Derivation of empirical formulae

The procedure followed to derive the empirical formulae from Figure F-1, can be summarised as follows:

- The degrees of hydration, in combined water to cement, of w:c ratios* 0,35, 0,50, 0,65 and 0,80, was determined graphically from Figure F-1. This was done at increments of 24 hours up to 1000 hours. This data is given in Table F-1.

* This range of w:c ratios covers almost the entire range used during this investigation, and it was not necessary to include w:c ratios < 0,35.

APPENDIX F - DERIVATION OF EMPIRICAL FORMULAE TO ESTIMATE THE DEGREE OF HYDRATION

- This data was converted to degree of hydration, as a percentage, by dividing the data of Table F-1 by 0,23 (Table F-2).
- The resulting data was plotted on a normal axis system and curves were fitted for the data (Figure F-2).

Table F-1: Degree of hydration (w_n:c) obtained from Figure F-1

Time (days)	w:c ratio			
	0,35	0,50	0,65	0,80
1	0,0805	0,0805	0,0805	0,0805
2	0,1084	0,1084	0,1084	0,1084
3	0,1147	0,1205	0,1279	0,1279
4	0,1174	0,1289	0,1368	0,1395
5	0,1205	0,1342	0,1453	0,1474
6	0,1211	0,1379	0,1495	0,1537
7	0,1226	0,1400	0,1526	0,1579
12	0,1268	0,1463	0,1624	0,1692
17	0,1295	0,1503	0,1687	0,1766
22	0,1314	0,1533	0,1733	0,1820
27	0,1330	0,1557	0,1770	0,1863
32	0,1343	0,1576	0,1801	0,1899
37	0,1354	0,1593	0,1827	0,1930
42	0,1364	0,1608	0,1850	0,1956
47	0,1373	0,1621	0,1871	0,1980
52	0,1381	0,1633	0,1889	0,2001
57	0,1388	0,1644	0,1905	0,2021
62	0,1394	0,1653	0,1921	0,2038

Table F-2: Degree of hydration (w_n:c) from the data of Table F-1

Time (days)	w:c ratio			
	0,35	0,50	0,65	0,80
1	35,01%	35,01%	35,01%	35,01%
2	47,14%	47,14%	47,14%	47,14%
3	49,89%	52,40%	55,61%	55,61%
4	51,03%	56,06%	59,50%	60,64%
5	52,40%	58,35%	63,16%	64,07%
6	52,63%	59,95%	64,99%	66,82%
7	53,32%	60,87%	66,36%	68,65%
12	55,12%	63,59%	70,60%	73,58%
17	56,29%	65,35%	73,34%	76,77%
22	57,15%	66,65%	75,36%	79,13%
27	57,84%	67,69%	76,97%	81,01%
32	58,40%	68,54%	78,31%	82,56%
37	58,89%	69,28%	79,45%	83,89%
42	59,31%	69,92%	80,45%	85,05%
47	59,69%	70,48%	81,33%	86,08%
52	60,03%	70,99%	82,12%	87,01%
57	60,34%	71,46%	82,85%	87,85%
62	60,62%	71,88%	83,51%	88,62%

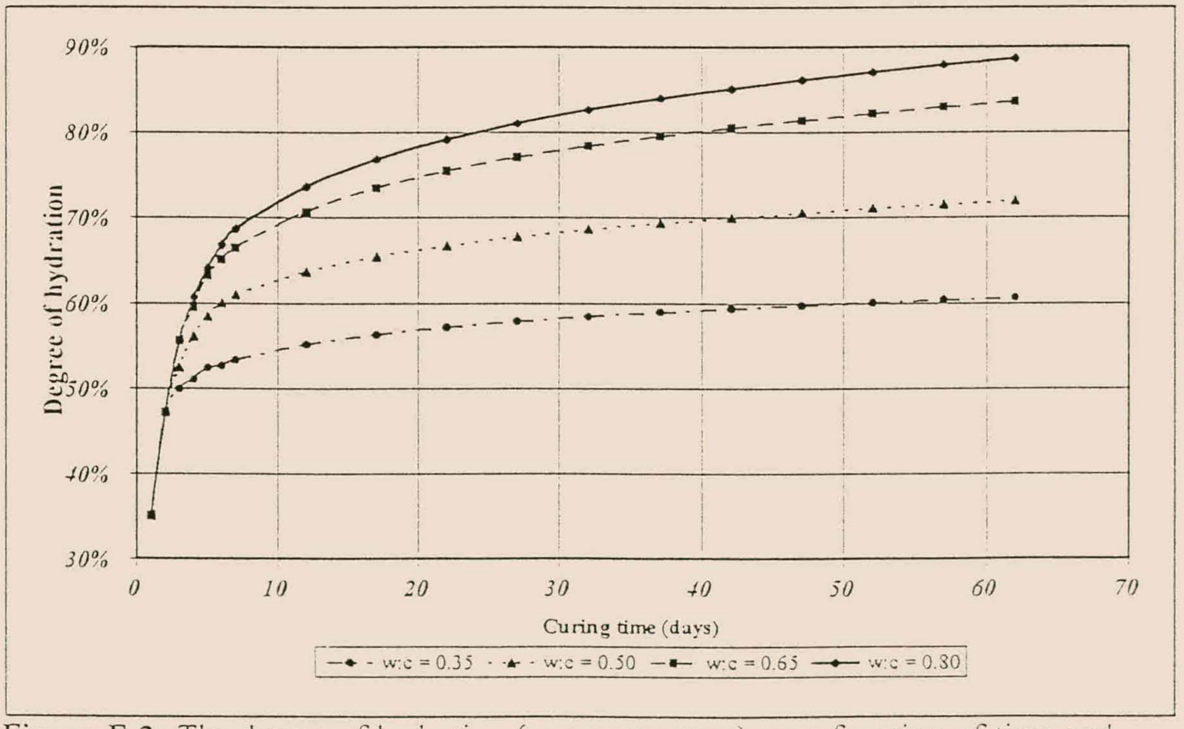

Figure F-2: The degree of hydration (as a percentage), as a function of time and w:c ratio (Table F-2)

- Empirical formulae were derived for the degree of hydration (α_e). This was done by fitting trend lines for the data of Figure F-2, and describing the variables of the trend lines in terms of time (t_e) and w:c ratio (w). These formulae are given in Table F-3.

Table F-3: Formulae for calculating the effective degree of hydration; as a function of effective curing period and w:c ratio

Effective period of wet curing (t_e in days)	Formula for effective degree of hydration (α_e)*
1	α_e = 35,01%
2	α_e = 47,14%
3	$\alpha_e = -0{,}1780w^2 + 0{,}3405w + 0{,}4007$
4	$\alpha_e = -0{,}4322w^2 + 0{,}7122w + 0{,}3136$
5 and above	$\alpha_e = (0{,}1376w - 0{,}015)\ln(t_e) + z$**

* These formulae are only applicable for w:c ratios ≥ 0,35

** z = 0,507 for w:c ratios ≥ 0,50

$z = 0{,}266w + 0{,}375$ for w:c ratios < 0,50

F.3. Comparison of the empirical formulae with the experimental data

In Figure F-3 the equations of Table F-3 are plotted as continuous lines, on the same axis as the data obtained from Soroka's data (represented by the data points). The derived empirical formulae provided good approximations for the original experimental data.

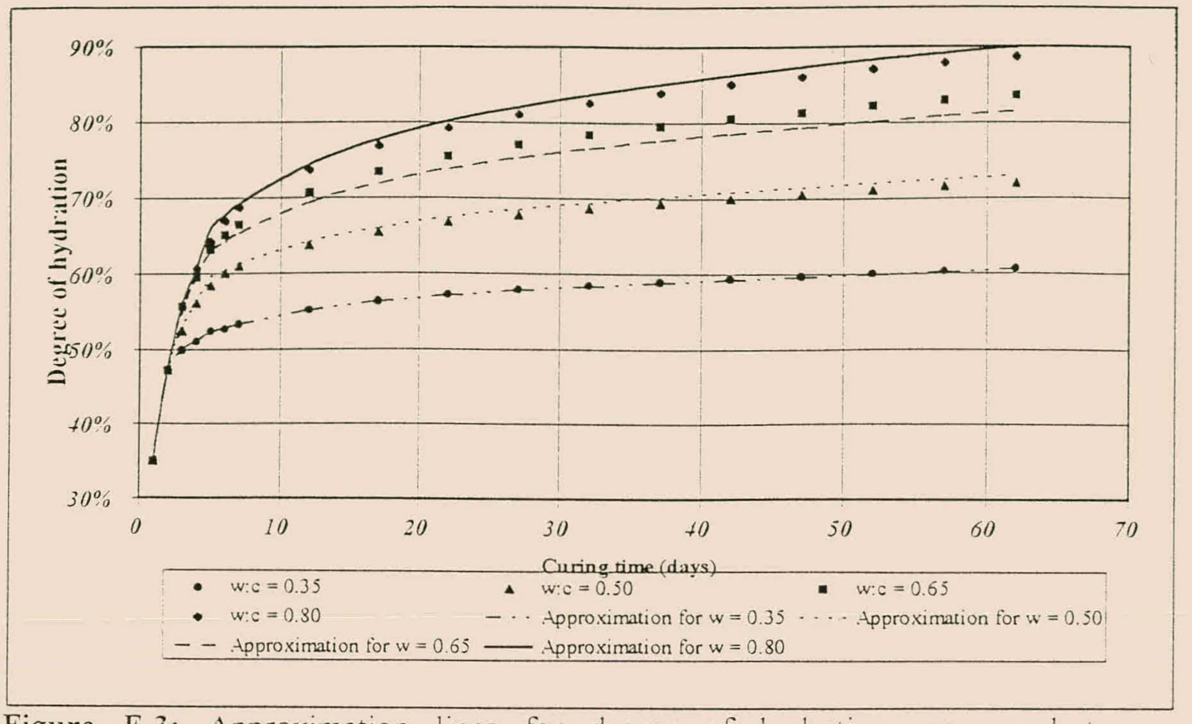

Figure F-3: Approximation lines for degree of hydration, compared to experimental data obtained [Soroka, 1979]